The Balancing of Steam Locomotives: A Dynamical Problem of the Nineteenth and Twentieth Centuries

by

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SUMMARY

Following a brief survey of the prehistory of balancing and its emergence as a technique of vibration control early in the nineteenth century, this thesis examines the problem of steam locomotive balancing. From 1845 when the investigations of the Gauge Commission highlighted the importance of the stability of the locomotive at speed the subject occupied the attention of British engineers for over a century.

The study examines the reasons for the persistence of the problem over such a prolonged period and the contribution of engineering science to the design of the locomotive.

The thesis deals with the identification of the dynamical problem, the development of a theory of balancing and its presentation to engineers. Also considered here are some locomotive examples and proposals emanating from engineers dissatisfied with the inherent instability of the conventional two-cylinder engine. The relationship between locomotive practice and balancing is then traced. Economic aspects of bridge maintenance eventually focused the attention of engineers on the nub of the issue and culminated in the work of the Bridge stress Committee, during the mid-1920s, which clearly exposed the significance of the dynamic interaction between locomotive and track, and led to the introduction of proper balancing parameters in locomotive design.

During the 1930s good balancing practice combined with

other rationalised design procedures enabled British express passenger locomotive practice to attain the peak of its achievement, although this was accomplished with three- and four-cylinder engines. Thereafter, the final phase of steam locomotion in Britain, which saw the production of the British Railways Standard Classes, convincingly demonstrated that with careful design it was possible to put powerful two-cylinder locomotives into service with hammer-blow characteristics considerably superior to those permitted in the recommendations of the Bridge Stress Committee.

Far from being resolved, however, the issue was directed once more to the effects of horizontal forces on the locomotive - its point of origin a hundred years earlier.

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Chapter 1

INTRODUCTION

1. Background to the study

One of the most striking aspects of the development of machinery during the nineteenth century was the phenomenal increase in operating speeds and, indeed, in men's concept of speed. This inexorable upward trend was a characteristic of modes of transport, machine tools, and processes alike. The evolution of engines created the opportunity to raise their speeds and hence obtain greater power without necessarily enlarging the size and mass of the components required for its generation and transmission.

Since, for a rotating body, the disturbing force brought into action increases as the square of the speed, the importance of operating speed in the design, construction and operation of machinery assumed a significance which grew throughout the nineteenth century and which has continued to the present day. Concomitant with the upward trend of speeds was the requirement for 'balancing' moving machine elements, and the emergence of this process as an engineering technique at the beginning of the nineteenth century and its growing importance as the steam engine was employed to drive an ever-increasing variety of machines. While the balance of rotating masses was relatively easily accomplished and its necessity perceived and met in earlier years, the problem of coping with the inertia forces of reciprocating masses was entirely a matter of the nineteenth century.

This study originated from an interest in the

application of 'engineering science' and its contribution to the evolution and the construction of machinery, and more specifically to the practice of 'balancing' as a pre-requisite for true-running and freedom from vibration in the operation of machines. The undesirable and potentially dangerous effects of vibration manifested themselves early in the last century and recurred with increasing frequency as the years passed. Essentially, vibration control became a major issue and received its first publicity as a specifically defined area of concern with the considerable attention devoted to the steadiness of railway locomotives in motion at the hearings of the Gauge Commission.[1] Thereafter problems of a similar nature arose in different fields of engineering activity and established the subject as one of common and fundamental importance. And this situation has persisted. Today, 'Vibrations' have ceased to be but one topic in a 'Theory of Machines' course and have become a subject in their own right and an integral part of many university and college courses for the education of engineers.

Initially it was intended that this piece of work would examine the origin and significance of the balancing problem, as one of the major sources of vibration and the methods adopted to solve it, in various types of machinery including electrical machines, internal combustion engines, locomotive engines, machine tools, marine engineering, stationary steam engines, textile machinery and turbines. However, it soon became apparent that such an undertaking was far too ambitious. In the first place the task was of such a magnitude that the time available for the necessary research did not permit such a

comprehensive investigation. Secondly, and undoubtedly of far greater moment for any historian of technology attempting to study a specific topic is the existence of the necessary evidence for appraisal and analysis and from which some meaningful conclusions could possibly be drawn. Preliminary enquiries to industrial companies, to museums and to record offices did not reveal the preservation of any such technical records nor did the responses provide any real basis for hope that such documents, etc., might have survived in anything but the most isolated and fragmentary manner.[2]

Of the various types of machinery listed in the preceding paragraph the railway locomotive can be distinguished from the other categories in one particular respect. Unlike other branches of engineering, for example marine engines and internal combustion engines, where the problem of dynamic balance was encountered, acceptable practical solutions[3] found with a consequent relatively quick disappearance of the topic from the deliberations of professional engineers, locomotive engineering is characterised by the persistence of the topic of balancing as a continuing theme virtually throughout the whole life of the steam locomotive as a railway traction vehicle. Unquestionably the nature of the problem had been clearly identified by the mid-nineteenth century but incredibly it persisted as a problem engaging the attention and discussion of engineers for over a century. And even then the matter was not settled. The need for more work, and the increasing importance of the subject, was articulated by senior engineers, civil and mechanical, as late as 1941.[4] An object of the thesis is to

examine the reasons for this remarkable state of affairs.

A major difficulty in undertaking a task of this nature, that is, a historical investigation of a specialised technical aspect of the design, construction and operation of steam locomotives is the fragmentary and disparate nature of the source materials available. Because locomotive design on a rational basis was never consistently assisted by the availability of good contemporary books on the subject by British engineers, it has not been possible to trace the history of this particular subject through a succession of 'standard' texts or through various, updated, editions of design manuals. Apart from D.K. Clark's Railway Machinery[5] which appeared in 1855, and was supplemented by Clark's co-authorship with Zerah Colburn in producing Recent Practice in the Locomotive Engine[6] five years later the works of W.F. Pettigrew[7] and C.E. Wolff,[8] which date from about the turn of the century, comprise the only substantial literature on the topic. The contribution of practising railway engineers to the literature of the subject is, likewise, somewhat limited and even their meagre literary output tends to be of restricted value to the reader in search of detailed information on any specific aspect of locomotive design. The majority of them, presumably under the weight of their professional responsibilities appear never to have had either the time or the inclination for such pursuits. Of the few who did, and the list includes such acknowledged names as Vaughan Pendred, E.L. Ahrons, H. Holcroft and E.S. Cox himself, who was responsible for the design of the last steam locomotives to be built for service on British metals, their books are

essentially general surveys for the technically-minded reader who wanted a comprehensive treatment of the subject rather than a specialised account of design philosophy and procedures. That there was such a demand cannot be doubted. By 1914 the series of articles 'Some Historical Points in the Details of British Locomotive Design' written by E.L. Ahrons for The Locomotive Magazine during 1908-9 was, at the request of the magazine's editor, revised and expanded for publication as a book.[9]

To this relatively small group of writers must be added another little band of men, including, for example, C.J. Allen, O.S. Nock, E.C. Poultney and B. Reed who were trained in railway engineering and subsequently turned to technical journalism. Often maintaining close personal relationships and friendships with the senior staff in railway companies and locomotive companies, they were knowledgeable and reliable critics of locomotive design and performance. But in studying their writings it must be recognised that their information was gathered and their interpretations made as keen spectators rather than as participants in the actual engineering processes. Inevitably this will demand a certain amount of caution in evaluating their comments because decisions made under the actual pressures of conflicting technical requirements, production facilities, material availability, time constraints, and so on are not always appreciated by the onlooker. Here, too, of course it must also be noted that the identical limitation of lack of detailed design analysis also applies to their work since they were writing for the same group of readers.

In attempting to examine the history of locomotive balancing, no simple task since the limited documentary evidence is fragmentary in nature and widely scattered, the approach has been essentially one of synthesis. This study has been based on a wide variety of evidence ranging from official government reports to anecdotal incidents[10] but drawing mainly on the Proceedings of both the Institution of Civil Engineers and the Institution of Mechanical Engineers together with the specialist journals The Engineer and Engineering. These varied sources seemed to offer a selection of evidence that could be studied and analysed and from which, perhaps, some conclusions could be drawn. The challenge was to determine the quality and nature of the evidence available to the historian seeking to pursue a specific but technically important aspect of locomotive design and operation and then, from this, to ascertain how the dynamical problems of the locomotive were perceived by the engineers involved and their response to them.

Before concentrating on the problems of the steam railway locomotive, however, a brief consideration will be given to the pre-history of balancing and its appearance in engineering literature at the beginning of the nineteenth century.

2. The Prehistory of Balancing: Rotary Motion

The importance of rotary motion in the processes of mechanisation, given an impetus and an enduring position as the foundation of present industrial societies during the period generally called the industrial revolution, requires little

emphasis. Nor do the remarkable subsequent developments in electricity generation, land and marine transport and aviation.

Imbalance is inherent in rotary motion which is a prehistoric invention. To 'throw' clay successfully a minimum speed of 100 revolutions per minute is required and so it appears that the potter's wheel, which is about 6,000 years old,[11] is almost certainly man's first fast-moving rotary device. Despite Childe's statement that 'Undocumented speculations as to how wheels might have developed [have] no place in history',[12] it does not seem unreasonable to conclude that early experience taught that if a wheel was to run smoothly it must possess symmetry about its rotational axis. By observation alone, prehistoric man could, and probably did, discover this condition. A natural achievement of symmetry was a direct consequence of the manufacturing process when, in due course, the lathe made its appearance and became an established tool in the hands of the craftsmen. Thus by classical times the production of various types of wheel, and also bearings, with an acceptable standard of operational performance was a commonplace achievement.

Probably, too, tests of a simple but effective nature were devised but of such procedures we have no knowledge and it is hardly worth speculating on the possibilities available to the contemporary craftsmen although the occasional, and rare, reference to such matters suggests that they were worthwhile and that the subject had received considerable thought and attention. Thus, Joseph Needham mentions a Chinese text, of perhaps the fourth century B.C., giving information on the

elaborate testing of completed chariot wheels by 'the use of geometrical instruments, flotation, weighing, and the measurement of empty spaces in the assembly by means of millet grains'.[13] Such sophistication, although hardly likely to have been anything other than exceptional, nevertheless reveals an awareness of the intricacies involved and the measures to be taken to ensure the desired result, that is, a wheel of high performance characteristics.

At a less-demanding level, and more generally, it seems reasonable to claim that, at a fairly early period, the wheelwright's art included appropriate methods of measurement and testing.

3. Grain Mills

During the first century B.C. continuous rotary motion was applied to grain and pulse grinding and remained the common practice until the second half of the nineteenth century when the introduction of roller mills brought about the steady but inevitable decline of milling with stones in Britain; the practice of which, nevertheless, persisted on a small but significant commercial scale until the time of the 1914-1918 War.

The grinding of grain by this method has confronted the millwright, from the earliest period, with the intricate mechanical problem of keeping the runner stone concentric with the bed stone, maintaining the grinding surfaces in virtually parallel planes with a carefully controlled clearance between them, whilst permitting the continuous feed of grain through the

mill. These requirements of the millstones used in water mills and windmills were, of course identical with those encountered in querns. To produce a uniform quality meal, that is, to achieve good grinding - and later, in large mills, to prevent the fire hazard of sparks generated by the stones running together -it was necessary for the runner stone to be dynamically balanced.

Again, progress via refinements made as the result of observation of the relationship between millstone and product seem to explain the developments in milling. This trend was assisted by the process of diffusion. In writing of Celtic querns in Britain J. Storck and W.D. Teague remark that one of the results of Roman influence was that 'stones became thinner and increased in diameter...but better balanced and supported.'[14]

The role of the Roman armies in spreading the use of the quern and the improvements in milling practice achieved by the Romans have also been briefly acknowledged by R. Bennett and J. Elton[15] and by L.A. Moritz.[16] In Rome, during the classical period, the appearance of flour in various grades is an indication of the attainment of a relatively high and sustainable control of the milling operation together with the associated sieving processes, the former being dependent in large measure on a satisfactory dynamic performance of the millstones themselves.

How regulation of the millstones was accomplished then, and throughout the ages, is not known with any certainty. The millwrights who built and maintained mills for something like

two thousand years probably learned their craft by experience as they moved from mill to mill or from one region to another, or by trial and error, or from rules-of-thumb which were transmitted orally from one generation to the next. Their knowledge did not find its way into books most likely because many of these craftsmen were illiterate and since, likewise, those to whom such works would have been of value were also unable to read there was hardly a demand or use for them.

Man's need of bread, a daily requirement, made milling an ever-present task and no doubt maintained interest in the process. It received considerable attention and literary expression in the works of Mariano Taccola,[17] Francesco di Giorgio Martini[18] and Agostino Ramelli,[19] for example. Martini's Treatise depicts some 67 different ways of driving millstones while of the 195 devices included in Ramelli's book, apart from 110 used for water-raising, the next largest group consisted of 21 grain mills, of which 20 possessed conventional millstones. These were variously operated by manpower, horsepower, waterpower and windpower. These, and other volumes by Renaissance authors, however, contain little practical, operational detail but even if they are regarded as no more than displays of the ingenuity of their authors their very choice of subjects is an indication of the importance attached to them and deemed likely to appeal to their patrons and readers as devices for the benefit of mankind.

A deficiency in practical technical detail may, in general, be said to characterise the somewhat later generation of books, specifically devoted to the subject of milling, by

British authors, such as those by John Banks,[20] Andrew Gray[21] and Robertson Buchanan.[22] Despite the rather theoretical nature of Banks' Treatise, with consideration given to topics such as centrifugal forces, centres of gyration and percussion, etc. it was no indication that milling was commonly based on 'science' or that millwrighting was institutionalised in the sense that it possessed a reference group comparable with the Institutions of Civil and Mechanical Engineers, for instance. Indeed it is unlikely that, as a group, British or even European millwrights possessed uniform views even on many fundamental points. This consensus could have been promoted by the availability of a practical technical literature on the subject but in Great Britain (and Europe) with enough millwrights living close enough together to be always at the service of the mills presumably there was not a perceived need for this. The New World, however, appears to have been confronted with a vastly different situation. In America with a shortage of skilled craftsmen of all types and much greater distances to be covered, the miller had to be more self-reliant and therefore the book was of practical utility in assisting him in his difficulties. It is not surprising to find that the more practical books on the subject are of American origin.

Oliver Evans's The Young Millwright and Millers' Guide,[22] first published in 1795 had reached its thirteenth edition by 1850 and by this latter date the writer distinguished between static and dynamic balance, emphasising the need for true balance to be achieved by 'running lead into the lightest side'.

No evidence yet appears to have come to the notice of historians to enable them to even approximately date when millstones were first 'balanced' by pouring molten metal into holes specially formed for this purpose but, in the absence of contrary evidence, it may be regarded as a post-medieval milling development. Since it was the middle of the nineteenth century before Evans referred to the practice in the later editions of his book, and allowing for the erratic and tardy rates at which innovations spread, it seems reasonable, based upon our present knowledge, to date the origin of this method of balancing the runner stone to the eighteenth or the early nineteenth century.

Likewise, Henry Pallett introduced the second edition of his book,[24] 'with considerable additional information and greatly improved and enlarged illustrations' in 1866 because the demand for the first edition had been 'so great and satisfactory'. Here, again, precise details were given about the location, shape and depth of hole into which molten lead was to be poured and his readers warned that failure to observe these points would lead to 'imperfect' balance when running.[25]

Correctly constructed and balanced millstones were seen to be important by these writers and probably by the more percipient of the millers and millwrights but good practice was not universal nor had the means of achieving it reached all ears. As late as the second edition of his book Pallett could state that some builders put blocks of burr, of varying thickness (some nearly twice the thickness of others) into the stones making proper balance almost impossible.

Variations in milling practice were clearly great with a

consequent wide range of mill operating efficiencies. Inferior methods were perpetrated through lack of knowledge and the slow diffusion of improvements. Both these points were made by John Sutcliffe who, in his Treatise on Canals and Reservoirs,[26] devoted a few pages to grain milling. His contention was that failure to adopt the 'balance rine' as opposed to the 'fixed rine' resulted in inexcusable, costly inefficiency and from a small consideration of milling costs determined that an annual saving of £1,250,000 was possible in the United Kingdom, but he concluded,

> ...few millers know of it, and still fewer know how to use it; which shows the necessity of making its utility as public as possible.[27]

Whilst the actual accuracy of his claim cannot be verified the point of his argument can hardly be denied. The hanging, balancing, and adjustment of the runner stone was clearly critical to its proper control and hence the satisfactory conduct of the milling operation. The exacting requirements of the stones in use has been described by Stanley Freese, a later commentator on the subject;

> Dressing, and subsequent re-balancing, of the stones is a fine art, on which much of the efficiency of the mill depends; indeed, it is claimed that the work should be so finished that the 'nip' or closeness of the stones

> will only permit of a piece of brown paper being placed between them at the centre, and a piece of tissue paper at the periphery.[28]

Although, no doubt, these incredibly fine limits prescribe a desired ideal rather than a realistic essential condition to be achieved it must be acknowledged that with runner stones of 4ft diameter, weighing about half a ton and rotating at 120 rpm, the importance of correct balance requires little emphasis.

It is, perhaps, indicative of the mounting pressure on millers to increase their output by reducing the time that the stones were out of action that in the years 1859 and 1860 three patents were taken out in Britain to simplify and quicken the process of balancing the runner stone by means of adjustable weights contained within boxes which, in turn, were set into the upper surface of the stone. Greater acuteness of the situation confronting millers in the United States probably accounts for the fact that two of these three designs originated there.

Henry Clarke,[29] a corn factor of Wakefield, Yorkshire, obtained a patent on behalf of Thomas Narburgh of St Louis, Missouri, whilst Alfred Newton,[30] a draughtsman at the Patent Office, carried out a similar service for John Fairclough, of Louisville, Kentucky. The third patent was granted to William Gough,[31] a miller from Birmingham.

These three patents, all based on the principle of providing quick and relatively easy adjustment of the plane in which the balance weights acted, show a significant advance in

an understanding of the true, dynamic, nature of the problem and both its technical and economic solution. Since the runner stone needed re-balancing every time the millstones were dressed the facility for easily modifying both the magnitude and the planar position of the weights offered great advantages over the older method of pouring molten lead into cavities in the top of the stone.

However, the appearance of the relatively sophisticated 'balance boxes' in runner stones during the later years of the nineteenth century came too late to have any significant impact on milling practice. The introduction of roller milling, during the 1870s, increasing urbanisation with the consequent depletion of the rural population, growth in grain imports - with the imported produce processed at the ports and then distributed via the well-established national railway system, were all factors which contributed to the decline of stone milling. And if the availability of the portable steam engine is taken into account the simultaneous decline of windmilling and watermilling is more readily appreciated.

By the time that millstones could be quickly and properly balanced their use on a commercial scale was effectively over. By the time the solution was found the problem had ceased to exist because the technology had been supplanted by a different and a superior method of grinding grain. A parallel situation may be discerned in the matter of balancing steam railway locomotives. The problem persisted for a hundred years and when, at last, it was rationally solved it, too, was irrelevant since steam traction was replaced by diesel

and electric power.

Far from being unusual, however, this appears to be an essential characteristic of technological development or evolution, and similar discontinuities may be envisaged in the transition from timber to iron in the construction of ships' hulls, for example, or in the adoption of steam turbines to supersede reciprocating steam engines for electricity generation, or in the decline of the glass thermionic valve in radio technology following the advent of the transistor. Reflection upon such issues emphasises the 'problem-solving' nature of engineering as an intellectual achievement of man quite distinct from 'science' with its search for understanding through general laws.

4. Windmills and Watermills

Although of crucial importance the millstones were not the only concern of the millwright with the problem of balancing.

It was necessary for the sails of a windmill to be balanced. To start a mill with common sails, each sweep in turn had to be brought down near the ground so that the cloth could be unrolled and spread across the bars. Likewise, to control the speed of the mill, the ordinary cloth-rigged sails were reefed with knots - like a ship's sail. For reefing, the mill had to be stopped successively with each sweep in the lowest position so that some of the canvas could be rolled up. Thus the operational need to bring any sail into its lowest position when required made balance an important matter.

Later developments, including Andrew Meikle's spring sail, invented in 1772, and patent sails, did not diminish the need for balanced sails because this was also necessary for smooth turning. And as Rex Wailes[32] has pointed out, although rotational speeds in England have been low, usually 12 to 16 revolutions per minute, tip velocities are high with the result that lack of balance imposes severe strain on the sails and shaft bearings.

Where necessary, the sails were balanced by fixing a piece of iron of convenient shape on to the whip[33] near its outer end.

The matter of sail balance also favoured the general use of four-sailed mills although multi-sailed mills with an even number of sails were built and could continue to work if one sail broke, by removing the opposite one of a pair to maintain the balance. Almost certainly multi-sailed mills were built to provide more power, and possibly greater ease of starting, rather than from any consideration of balance. Clearly this latter point was not deemed important by John Smeaton, who had conducted experiments on the design of sails and progressed from the conventional four-sails to five sails in his last three mills, despite the inherent disadvantage that serious damage to a sail rendered the mill completely unbalanced and unworkable. His assessment of operational requirements obviously convinced him that the advantages to be derived from his design when the mills were working conclusively outweighed the consequences of a mill being completely out of action.

Somewhat incongruously, perhaps, E.L. Hill introduced a

paper[34] on balancing railway locomotives, given at the Institution of Civil Engineers in 1891, with a reference to the balance of wooden water wheels. He stated, without any indication of the source of his information, that one of the earliest instances of balancing was to keep wooden water wheels turning very slowly instead of stopping them altogether since, if they were allowed to stop for any length of time the part above water would dry out while that below would remain wet, so that the wheel on starting again would run in a succession of jerks, being heavier on one side than the other. Undoubtedly this irregular motion would occur in the circumstances described but almost certainly a reason other than balance would account for the practice.

Improved balance of a wooden water wheel came as a natural and beneficial consequence of keeping the wheel wet rather than being the reason for maintaining it in that condition. Our present knowledge of water wheels does not seem to permit any other conclusion on this point and in the absence of reliable evidence to the contrary not only must Hill's claim be questioned it can only be cautiously accepted as an incomplete and inaccurate interpretation of his source material.

Due to dimensional inaccuracies in wheel fabrication resulting in lack of symmetry about the rotational axis, and inconsistency in the materials of construction, unbalanced water wheels were not unknown. The defects could be found in both wooden and iron wheels and were remedied by the use of balance weights. Millwrights, even in the 'iron age' of millwrighting, did not have recourse to science but proceeded, as their

predecessors had done, by empirical means. They knew when a wheel was not running truly and smoothly and with their craft knowledge and skills they also knew how to make it do so.

5. The Lathe: 'Balancing' enters history

When the lathe was used to cut metals the impetus to achieving continuous rotation became critical. Continuous drive gave possibilities for development; by the use of suitable pulleys the rotational speed of the workpiece could be substantially increased and also varied to suit the turner's needs, thus enlarging the scope and the flexibility of this basic machine tool.[35] But higher speeds were accompanied by the possibility of difficulties arising from the lack of dynamic balance.

The application of a small steam engine to drive a lathe in the workshop of the Earl of Craven, at Combe Abbey, in 1810, provides us with the first clear and documented evidence of the ill effects of imbalance. Details of the incident were related by Dr J.B. Melson, in the sixth of a course of nine lectures on Physical Mechanics given at the Birmingham Philosophical Institution on 28 March 1842. The Syllabus for these lectures is shown in Fig.1.1 This was possibly the first public lecture on the topic and is the earliest evidence of the subject being so presented that this piece of research has revealed.

There are no transactions of the Philosophical Institution and our knowledge of the lecture is based on a report in the Midland Counties Herald[36] which was subsequently extensively quoted in the Mechanics Magazine. Later, J.E.

BIRMINGHAM PHILOSOPHICAL INSTITUTION.

SYLLABUS

OF A

COURSE OF NINE LECTURES

ON

PHYSICAL MECHANICS,

BY

JOHN BARRITT MELSON, A.B., M.D., F.C.P.S.,

Corresponding Member of the Philosophical Society of Basle; Lecturer on Natural & Experimental Philosophy in the Royal School of Medicine and Surgery, and Physician to the Queen's Hospital, Birmingham.

EACH LECTURE WILL COMMENCE AT HALF-PAST SEVEN O'CLOCK PRECISELY.

LECTURE I.—Monday, February 21, 1842.

An outline of the History of the Physical Sciences.—*Nature of the Course.*

LECTURE II.—Monday, February 28.

THE GENERAL PROPERTIES OF MATTER.—*Extent.—Impenetrability.—Porosity.—Divisibility.*—Is matter infinitely divisible? Atoms—The theories of Lucretius, Gassendi, Wolf, Swedenborg, and Berkeley.—*Elasticity.—Compressibility.—Mobility.—Inertia.*—Universal attraction—Molecular attraction and repulsion.

LECTURE III.—Monday, March 7.

ATTRACTION *continued.* Cohesion—Capillary attraction.—Endosmose.—Exosmose.—Gravitation—Centre of gravity.—LAWS OF MOTION.

LECTURE IV.—Monday, March 14.

LAWS OF MOTION *continued.* Equilibrium—Composition of forces—Effects of gravitation—Vertical descent of bodies.—Attwood's Machine.—Projectiles—Descent on an inclined plane—Curvilinear descent.—Momentum.—Impact.—*The Pendulum*—Cycloid—Centres of oscillation and percussion.

LECTURE V.—Monday, March 21.

THE MECHANICS OF SOLIDS. *The Simple Machines.* The Lever—The Wheel and Axle—Pullies—Inclined Plane—The Capstan.

LECTURE VI.—Monday, March 28.

THE MECHANICAL POWERS *continued.* The Wedge—The Screw.

FRICTION AND BALANCING. Heston's Experiments.

LECTURE VII.—Monday, April 4.

MECHANICS OF GASEOUS BODIES.—PNEUMOSTATICS. Principal aëriform bodies.—THE ATMOSPHERE.—Its height, pressure, and elastic force.—Barometer.—Law of Marriotte.—Experiments with the Air Pump.

LECTURE VIII.—Monday, April 11.

THE MECHANICS OF FLUIDS.—HYDROSTATICS. Laws of fluids at rest.—Pressure.—Equilibrium.—Equilibrium of floating bodies. Specific gravity, how ascertained, of bodies solid, fluid, and aëriform. *The Hydrometer.* Hydrostatic Bellows. Natural fountains and springs.

LECTURE IX.—Monday, April 18.

THE MECHANICS OF GASES AND FLUIDS *continued.*—PNEUMO-DYNAMICS. Phenomena of the Winds. Elastic force of Steam.

HYDRO-DYNAMICS.—Artificial fountains.—Pumps. Siphons. The movement of fluids through orifices, tubes, and canals. The reciprocal action of liquids and solids. Mr. Rofe's experiments. Bramah's Press. Waves.—Tidal Observations.—Conclusion.

NON-SUBSCRIBER'S TICKET TO THE COURSE, £1. 1s.

*** Gentlemen subscribing £1. 11s. 6d. annually, are entitled to personal admission to the News-room, and a Transferable Ticket to the Lectures, Museum, and Library of the Institution.

Subscribers of £1. 1s. to a Non-transferable Ticket to the Lectures, Museum, &c. &c.

Ladies subscribing £1. 1s. per annum, are entitled to a Ticket to the Lectures, Museum, &c. transferable amongst Ladies only.

Printed by James Belcher and Son, High-street, Birmingham.

Fig.1.1 Syllabus of a Course of Lectures at the Birmingham Philosophical Institution

McConnell, Vice-President of the Institution of Mechanical Engineers, introduced his first paper[37] to the Institution entitled 'On the Balancing of Wheels' with a lengthy extract from this report.

We learn that the lathe was kept by his lordship for the amusement of himself and his visitors in the practice of mechanical pursuits. The Earl and 'many of his visitors' were surprised to find that when the speed of the lathe was raised to about 600 revolutions per minute it began to shake, and shook to such an extent as the speed was increased that the whole lathe and its frame jumped from the floor.

Mr George Heaton, an engineer, of Shadwell Street Mills, Birmingham, then in the service of the Earl, was consulted as to the cause of the vibration and unhesitatingly attributed it to the imbalance of the revolving parts of the machine. This he remedied by boring a hole in the light side of the pulley, three and a half inches from the centre and inserted nine ounces of lead, the requisite amount to achieve 'perfect' balance of the pulley. Thereafter, at a speed of 600 rpm and any other speed required for its work, the motion of the lathe was undisturbed by vibration.

A reason for the fault was also conjectured, '...it was probable that the texture of the wood being closer on one side than on the other when dry was the cause of this inequality in the weight.'[38]

In this statement the word 'texture' is not unambiguous but it appears to refer to the density of the timber, rosewood in this particular case. We have no dimensional information

about the pulley but within a single piece of rosewood the density variation would not be significant. It would not require the nine ounces of lead necessary to restore balance. Most likely the cause of imbalance was due to the irregular shrinkage of the timber displacing the mass centre from the rotational axis. Such a phenomenon would not be unusual where only partly seasoned timber was used and this explanation is consistent with the implication that the variation only developed when the wood was dry. However, a difficulty arises with this interpretation because the report claims that the lathe was of beautiful workmanship and made by one of the best makers in London and so to accept it leads to the conclusion that the maker, a skilled craftsman, was prepared to and did use unseasoned timber and also that he was not aware of the possible consequences of doing so. Although the former seems improbable, we have no knowledge of the history of the pulley after it was manufactured and it may have been exposed to conditions that could have affected its stability, the latter is distinctly possible since at the very beginning of the nineteenth century it is by no means certain that the necessity for good rotary balance was universally recognised or practised. Testimony to this is provided by Dr Melson who, in introducing his lecture, referred to above, stated 'There is not among machinists sufficient care taken to construct all revolving machinery as nearly as possible in balance.'

To illustrate this thesis he described how Heaton had been called in to solve problems of uneven motion in guide pulleys used on railways where rope was employed to draw the

train along, and to correct deficiencies of operation in both light and heavy machinery. He cited the case of a fan required to run at 1,000 rpm (but found incapable of doing so) to provide a blast for melting iron which tore itself from its foundations, shook the whole building and disturbed the neighbourhood to such an extent that the proprietors were threatened with prosecution for nuisance. This was but an early illustration of a problem that was to recur on a more serious scale fifty years later when reciprocating steam engines were used to drive electrical generators. London experienced the vexation in good measure. Vibration troubles at the Manchester Square power station actually led to litigation,[39] and similar problems were also encountered at other generating plants including Bankside, Leyton and Mason's Yard. Those at the Greenwich station affected instruments at the Observatory half a mile away.

Having dismantled the troublesome fan, Heaton found it to be two and a half pounds out-of-balance and the fault was rectified with satisfactory results, the machine being able to run at its intended speed without displaying any tendency to wander from its moorings. Probably 'out-of-balance effects' of this magnitude were not uncommon in the 1830s and 1840s, and even much later. The many exacting requirements of satisfactory sandcasting were not appreciated and not attainable at that period. Lack of homogeneity due to blow-holes, caused by furnace gases dissolved in the metal during the melting process or by chemical reactions occurring in the molten metal, has always tended to make such castings one of the most unreliable metallurgical structures. And a century later this point was

emphasised in connection with locomotive balancing. In his paper[40] on locomotive balancing read to the Institution of Locomotive Engineers in 1938 D.C. Brown stated that one of the principal requirements was to ensure that the wheels as cast conformed to the designer's specification. Porosity often resulted in balance weights being light and requiring correction.[41]

6. Heaton's Steam Carriage

From the late 1820s the application of the reciprocating steam engine to locomotive uses created a new situation involving dynamical problems which manifested themselves in an unmistakable and forceful manner.

Again, the first clear evidence comes from the work of George Heaton and his brothers who invented and patented[42] the design for a steam-propelled road carriage. An illustration of this occupied the front page of Mechanics Magazine on Saturday, 14 September 1833. The drawing shown here, Fig.1.2 is from the original drawing in the Birmingham Reference Library. Such was the confidence in the vehicle and its commercial viability that in October 1833 a business was formed under the name of 'The Birmingham General Steam Carriage Company' and within twenty-four hours three thousand out of the total of five thousand shares had been sold within the town. However, the initial optimism was not sustained and the affairs of the Company were wound up on 27 January 1836. Throughout its existence, its Chairman was Henry Merry and in 1958 Miss D.T. Merry donated the minute book and the correspondence of the

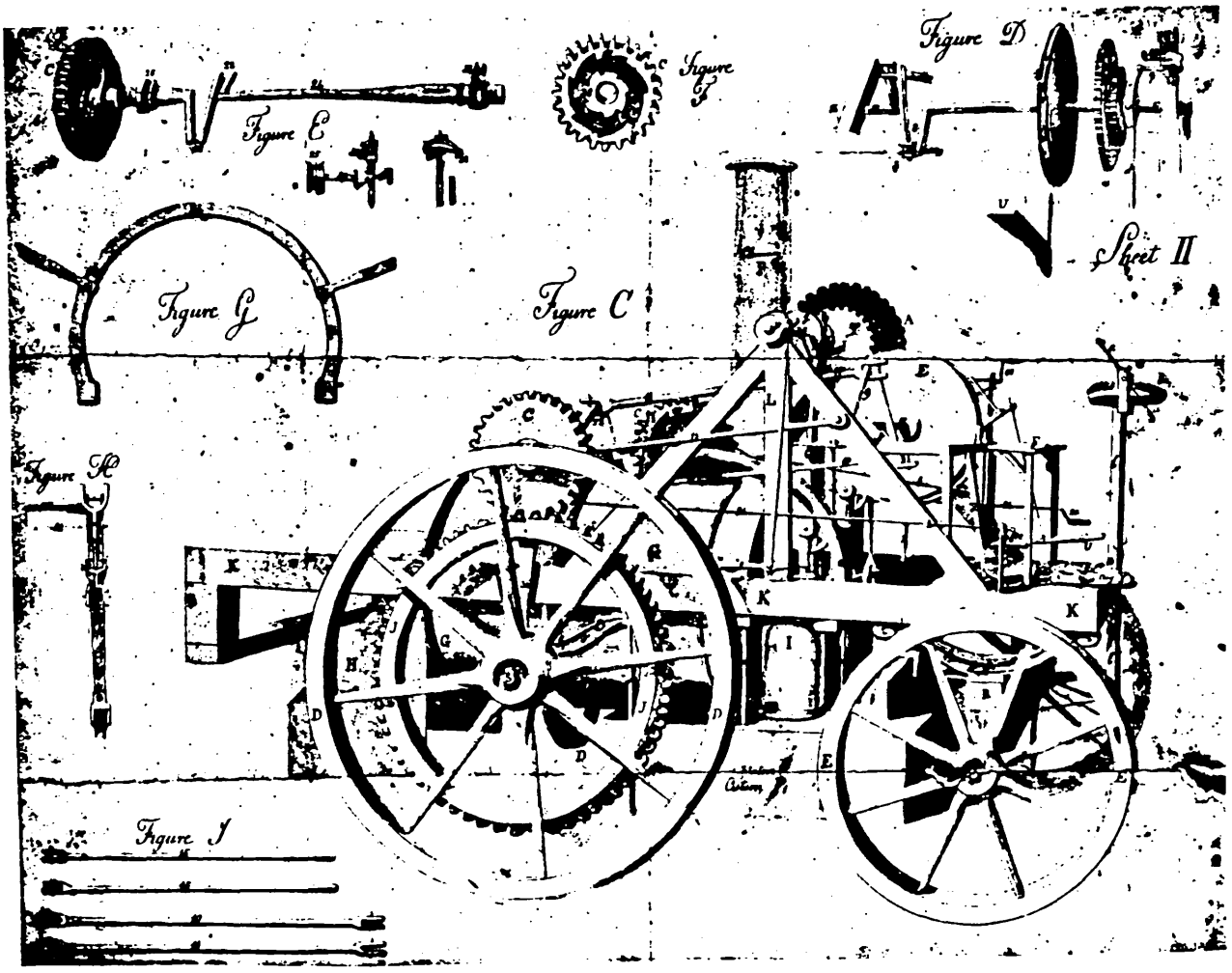


Fig.1.2 Heaton's Steam Carriage, 1830

Company to the Birmingham Museum of Science and Industry.[43] This contains a letter from Heaton Brothers, dated 11 April 1834, which is the only genuinely contemporary document relating to the engineering work of their business that this study has revealed. Its subject matter concerned the results of tests which were not successful,

> ...convince us that it is improbable that our machine will work to profit on the Common Road with the steam at such a pressure as will be safe for the public to trust.

Factors other than steam pressure account for the lack of success of the steam carriage at this period and have been briefly discussed in an article by F.T. Evans.[44]

Prudently and honestly Heaton Brothers admitted their failure and abandoned the attempts to apply steam power to road carriages, but not before a valuable lesson had been learned. During their early trips it was found that the engine was so unsteady when working at 160 or 180 strokes per minute, that it was impossible for the men to keep their seats. They observed,

> Being aware that this motion could only be produced by some portions of our machinery being out of balance, we placed a compensating weight opposite each crank, and repeated our former experiment upon the same road and found we attained greater speed with no greater

> consumption of fuel, and the machine travelled perfectly steady at any speed, and free from any symptoms of rocking or shaking.

This brief comment, our first recorded evidence of the dynamical problems associated with the reciprocating mechanism, gives no indication that the true nature of the trouble was perceived. It does, however, suggest that the source of the bother had been identified, the matter given some attention, and an empirical solution found and, indeed, one that was in the course of time to be applied to the counter-weighting of locomotive driving wheels. But, seemingly, this expedient did not satisfy George Heaton for, as Chapter 4 will show, he devised and patented a 'theoretically correct' solution to the problem of balancing reciprocating masses.

Unquestionably George Heaton is a man of some importance in the early history of balancing in this country since, from his efforts in 1810 he appears to have devoted a major part of his life's work to the study of the subject and to effecting proper balancing in machinery of all kinds. Unfortunately virtually nothing is known of him, but the few biographical details acquired during the course of this study are presented in Appendix 1.

By the middle of the nineteenth century the consequences of imbalance were unmistakably manifesting themselves throughout industry. Heaton's experience of being summoned to diagnose and correct deficiencies in machinery of all kinds, together with the fact that McConnell chose to address the recently formed

Institution of Mechanical Engineers on the importance of properly balancing machinery, provides clear evidence that at this period many of those who designed, manufactured, operated and maintained machinery had no real awareness of the significance of the topic.

Chapter 1

INTRODUCTION

References and Notes

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2. This situation is typically illustrated by the Archives Department of Courtaulds Limited, in connection with the development of textile machinery and by the Avery Historical Museum on the subject of balancing machines. W. & T. Avery Limited, although more widely known as manufacturers of weighing machines, was the most prominent British producer of balancing machines during the 1920s and 1930s.

   The former Company 'do not have any records' while the latter, with one or two undated photographs 'regret that our records have fallen short on this aspect of Avery products, but they are outside the normal scope of the museum, which concentrates on 'The History of Weighing'.

Likewise, the early records of Samuel Courtauld & Co. Ltd which are deposited in the Essex County Record Office, deal with matters such as factory administration and operation, staffing, wages, etc. and are devoid of technical records.

3. See Chapter 3, section 12.a.

4. These views were expressed at a Joint Meeting of the Institutions of Civil and Mechanical Engineers in December 1941. The two papers 'Hammer-Blow in Locomotives: Can it not be Abolished Altogether?' by Colam, Sir H.N. and Watson, Major J.D. and 'Balancing of Locomotive Reciprocating Parts' by Cox, E.S. are considered in greater detail in Chapter 7.

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10. It could be argued that the anecdote has no place in a serious historical study and few would dispute that as a technique in which a small number of examples is offered

as proof, it is unacceptable. And yet in the peculiar circumstances in which the historian of technology finds himself it might possess a small but justifiable place.

That mechanics and engineers were, and essentially still are, practical men not inclined to literary work is a fact so well known as to need no further elaboration here. Their reluctance (or in earlier days, inability) to record their views, opinions, reasons, decisions, etc. leaves the historian with no alternative but to offer little more than conjecture, or even qualified guesses, on many points. In this situation when a conjecture can be supported by an anecdote the corroborative value of the latter is not to be summarily dismissed. This point is illustrated, in connection with the apparent lack of knowledge of performing balancing calculations and O. Bulleid's experience as Nigel Gresley's assistant, in Chapter 5.

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33. The 'whip' is the main longitudinal framing member of the individual windmill sail.

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Chapter 2

THE RAILWAY LOCOMOTIVE

1. Early Locomotives and Speed

There are many varied disturbing forces connected with the running of a steam locomotive along a track and it took a number of years before the consequences of imbalance were isolated from the rest. When, in 1812, John Blenkinsop and Matthew Murray produced the first two-cylinder locomotive with the cranks at right-angles they initiated a design principle which, years later, became established and subsequently persisted throughout the entire history of the steam locomotive. This feature was responsible for the related problems of unsteady motion of locomotives and recurring damage to the track. Design variations characterise this embryonic stage of locomotive development as engineers grappled with the unprecedented problems of adapting the high-pressure steam engine to tractive use. During the early years when a number of locomotives followed the Blenkinsop and Murray arrangement of two vertical cylinders partially immersed into the boiler and on the boiler centre-line (and this disposition of cylinders was used by George Stephenson for 'Locomotion' in 1825) the design was adequate. Coal haulage at slow speeds was the functional requirement and although the enginemen must have been conscious of the up-and-down heaving of the vehicle as the pistons reciprocated the cylinder layout minimised the tendency of the locomotive to 'nose' its way along the track.

Once the cylinders were moved from the central position the consequences quickly revealed themselves. John Dixon,

surveyor of the Stockton and Darlington Company, informed his brother James, in a letter dated 16 October 1829 that Hackworth's 'Sans Pareil' "...rolls about like an Empty Beer Butt on a rough Pavement..."[1]

This locomotive had its two cylinders mounted vertically outside the boiler, at the rear of the engine and driving via connecting-rods on to crank-pins on the rear wheels which were coupled to the front wheels. This cylinder arrangement with disturbing forces acting alternately on each side of the vehicle would have maximised the rolling tendency and Dixon's apposite comment on the behaviour of this Rainhill contestant can hardly be doubted. However, even the victor in these Trials, the 'Rocket' displayed a significant 'shouldering' motion when it was run at speed and led the Stephensons to adopt the expedient of reducing the inclination of its cylinders, from 35° to 7°.[2]

During 1830, Bury and Kennedy's locomotive "Liverpool' and Stephenson's 'Planet' appeared, both with horizontal cylinders, and this layout, whether the cylinders were 'inside' or 'outside', became the predominant form. By this time, then, the combination of two cylinders, with cranks at right-angles, in a low-down horizontal position had cast the die for what was to prove to be the most widely used form of steam locomotive.

A dynamical consequence of this design was the tendency of the locomotive to oscillate from side-to-side as it travelled along the rails, with wheel flanges alternately grinding against one rail and then the other, together with a variation in draw-bar pull. The result of these two effects, besides its deleterious effect upon locomotive, train and permanent way was

transmitted to the passengers as an unpleasant and uncomfortable jarring and vibration. Minimisation of these effects was the reason for balancing the reciprocating masses of the locomotive and once this fact was recognised and accepted the subject became a matter for consideration and discussion among railway engineers until the 'end of steam'.

Since these disturbing forces increased in magnitude as the square of the speed, rather than as with the speed itself, operating speeds were of crucial importance in the safe running of public railways. Early developments quickly changed people's ideas of realistically attainable speeds. Concentration on the immediate tangible effects of the new transport system tends to mask a significant psychological impact. Suddenly man was confronted with an entirely new concept, that of speed. Well into the nineteenth century man's rate of movement was restricted by his own muscle-power or by that of the horse and, no doubt, his thoughts on the subject were conditioned accordingly. Universally, the common experience of mankind knew nothing faster. A natural consequence of this was the incapacity to think about the matter and to conjecture on its possible increase, a limitation naturally shared by the early locomotive engineers themselves who did not anticipate the impending dramatic and far-reaching developments. Nor did the transport scene in the mid-1820s suggest the likelihood of any marked change in the situation. In 1825 the Parliamentary opponents of the Liverpool and Manchester Company's first Bill made much of the fact that in terms of speed the locomotive was inferior to the horse-drawn coach which was then running on

important roads at 9-10 mph.[3] Clearly, the advocates of the railway did not imagine that this speed would be appreciably exceeded.

Nicholas Wood, a professional engineer and an authority on early railways, published in 1825 what can be accepted as a considered and responsible view of envisaged locomotive speeds when he wrote

> It is far from my wish to promulgate to the world that the ridiculous expectations, or rather professions, of the enthusiastic speculist will be realised, and that we shall see them travelling at the rate of 12, 16, 18 or 20 miles an hour, nothing could do more harm towards their adoption or general improvement than the promulgation of such nonsense.[4]

Four years later, in 1829, the Rainhill Trials revealed both the under-estimation of actual attainable speeds by Woods and also a demonstration of the potential for higher speeds of the steam locomotive. Whereas the original conditions for these trials stipulated that the engine, if it weighed six tons, should draw a train of gross weight of twenty tons on the level at 10 mph, this speed was exceeded by 'Rocket' on the very first day of the competition.[5] During the period of these trials 'Rocket' made two runs, without a tender, at 30 mph while 'Novelty' in an exhibition run hauled a carriage with about forty-five passengers at 30 mph.[6] Furthermore these speeds, far from being exceptional were very quickly destined to become

customary. So rapid was the potential for increased speed realised that by 1830, on the Liverpool and Manchester Railway, 30 mph was being peaked in daily service.[7] Not surprisingly, when the second edition of Wood's book, quoted above, was published in 1831 this reference to speeds was omitted. Later in the 1830s speeds of 40 mph although in many instances unsafe, were not uncommon and the trend was inexorably upwards. In these circumstances the impact of speed-related vibration problems was dramatic and crucial.

Unquestionably the emergent public railway system confronted the entire nation with an unprecedented and an unparalleled experience during the fourth and fifth decades of the nineteenth century.

To the engineers fell the immense technical tasks of establishing, maintaining and operating a complex transport system that was in a state of continuous expansion. Previous experience of railways, where it existed, was of limited use. Conditions were vastly different from those described by C. von Oeynhausen and H. von Dechen in their survey[8] of English railways in 1826 and 1827. The short, light rails of cast-iron and wrought iron used for the tracks of colliery and quarry railways reported on by these mining engineers were never even contemplated for the Liverpool and Manchester Railway. And, as mentioned in Chapter 6, this railway had, in the light of experience, to double the weight of its rails within ten years of commencing operation.

In the welter of problems with which the locomotive engineer had to contend the stability of the engine on the track

was to emerge, by the time of the Gauge Commission in 1845, as a prominent and urgent issue. Quite apart from the unsteadiness of motion attributable to the track itself, including rail joint effects, gauge variation, inadequate foundations, subsidence and the defects caused by climatic conditions, there were several features of the locomotive itself which were not conducive to smooth and undisturbed motion along the track.

2. Accidents

William Huskisson's tragic and untimely end on the opening day of the Liverpool and Manchester Railway was a poignant indication that users of this mode of travel were exposed to risks to life and limb. Whatever its advantages and merits, passengers were threatened by new dangers. Unequivocally, these were expressed by Thomas Creevy after his five mile journey at 20 miles an hour in November 1829;

> ...it is impossible to divest yourself of the notion of instant death to all, upon the least accident happening.[9]

From the beginning of public services in the early 1830s accidents (mainly derailments and collisions) involving passenger fatalities occurred and aroused public fears and concern for the safety of railway transport. Such unfamiliar and erratic contraptions as the early locomotives can hardly have commended themselves to the public as the power units of a reliable, safe and comfortable means of travel. It is against

this background of accidents and worries over safety that the problem of locomotive balance must be seen. It was not just a mechanical problem, although it was certainly that; it was also a danger.

Ideas of safety appear to have developed slowly and a proper examination of this topic would call for a separate extensive study because it involves virtually all aspects of railway operation and ranges from simple human actions to complex technical issues. However, it is worth commenting in passing that notions of safety originate from the railways. Prior to the railway period failures and disasters appear to have been regarded as bad luck or as Acts of God whereas the railways brought to the fore the idea that accidents were the result of bad design, mismanagement, or other aspects of human behaviour. Culpability and legal liability became a reality. It is reasonable to assume that from the outset railway companies in general have conducted their business professionally. Since loss of life, injury, and inconvenience to customers with the associated financial burdens of compensation, replacement and repair, together with the adverse publicity, reduced their potential profitability they have always had the incentive to treat safety responsibly and seriously. However, scarcely a year passed without a train accident in which passengers lost their lives.

In 1840 six separate accidents claimed fifteen lives, the following year three accidents claimed a total of fourteen lives and in 1844, between 28 August and 21 November, four accidents claimed another six lives.

The anxiety aroused by this state of affairs and the prominence given to these accidents by the press led to the demand for legislative control of railway operation. Such clamour was not welcomed by engineers and was specifically repudiated by I.K. Brunel who was of the opinion that engineering matters were best left to engineers. Not, of course, that all of these accidents could be directly attributed to technical faults and failures. Nevertheless, as the railway system itself was a new and newsworthy national development with opponents and critics besides protagonists its failures and deficiencies received maximum publicity, much of it biased and unjustified. A Select Committee on Railway Communication was appointed in April 1839, the first parliamentary inquiry to investigate railway questions in general. The witnesses who appeared before it were of the opinion that some governmental board of control for railways was necessary. Government action came the following year with the establishment of the Railway Department as a branch of the Board of Trade. Although empowered by the authority of Parliament it was not intended that the Board should have any right of control or regulation in the operation of a railway company unless requested by the company. Further legislation, intended to secure better inspection of railways before their opening, followed with the Regulation of Railways Act of 1842. While neither of these two Acts sanctioned inquiries by the inspecting officers into the causes of accidents, such inquiries were held, the first being into the fatal derailment on 7 August 1840 at Howden, on the Hull and Selby Railway when five passengers were killed.

Reports on accidents, however, were not made public until they appeared with the annual reports of the officers of the Railway Department.[10]

These early reports are bereft of detailed analyses and, in general, merely indicated major contributory factors -frequently excessive speed and defective track - or sometimes they say simply 'cause unknown'. Nor were some of the inspector's recommendations particularly useful or appropriate to the rapidly developing railway system, as may be appreciated from the report,[11] signed by Sir Frederick Smith, the chief inspecting officer of railways, on the accident which occurred on the Brighton Railway on 2 October 1841. Here, the derailment at Cuckfield, in which four passengers died was attributed to high speed and "...partly to the defective state to which the Road has been reduced by the long continuance of heavy rain."[12]

The inspector called the attention of the London and Brighton Company to the necessity for a considerable reduction in speeds on falling gradients and of paying constant and close attention to the state of their track. He also urged cessation of the practice of double-heading; especially when the leading locomotive was the lighter of the two and had only four wheels. He then referred to a most important and very safe practice on some of the northern railways which he recommended should be immediately introduced on the Brighton line and ought to be adopted on all lines of recent construction

> ...that of making each Policeman carry a gauge and walk over his beat before the arrival of every train, trying

> the gauge of the rails in such a number of points as to ascertain whether the line is throughout in perfect order, and it is the Policeman's duty to stop a train or give the signal of caution, according to the degree of risks he may discover.[13]

One trembles at the awful responsibility so inappropriately and so unwarrantably, and yet seemingly so casually, placed on the shoulders of the policeman. Furthermore, this precaution advocated with the full authority of the chief inspecting officer of railways was an expedient of limited value. Apart from most obvious defects of lack of gauge, broken rails and chairs, ground subsidence or other manifest sources of danger, for example, a policeman could hardly have been expected to assess the consequences of a locomotive and train, weighing many tons and travelling at high speed, moving over any section of the permanent way.

Accidents at this period were attributable to a variety of causes. The engineers and inspectors involved lacked experience in the technology of the new, rapidly growing transport system - a deficiency which only time could give them the opportunity to remedy - and methodical investigative procedures had yet to be formulated. Additionally, and pertinently, theoretical aspects of railway engineering were still undeveloped. Even in those instances where faulty locomotive running was deemed to be the major cause of a mishap, these reports give no indication that men such as Sir Frederick Smith, Professor P. Barlow, I.K. Brunel and other prominent

engineers grasped the true, or rather the main, reason for the irregular motion of the locomotive which preceded the accidents. This seems to have dawned on them slowly, over the years, as other assumed reasons for the unsteady motion were successively eliminated from their reckoning or relegated to a lower degree of significance.

3. The Stability of the Locomotive

Numerous factors and effects contributed to the lack of stability of the locomotive in its motion along the track and the identification of the causes due to unbalanced masses and forces was not quick. Despite J. Bodmer's patent[14] of 1834, suggesting that he perceived the true nature of the problem associated wih reciprocating masses at an early date, other engineers were not aware of its significance at this time or alternatively, they recognised the source of trouble but considered that the situation had not developed to the stage where separate counter-balancing provision was required. Most likely the dynamic effects of reciprocating masses were not appreciated. Nor is this surprising in the circumstances. Confronted with the immense tasks of building and operating the new and rapidly developing railway transport system, inadequacies and failures had to be analysed and experience gained before design ideas and practices could be refined, problems identified and improvements incorporated into the system. These processes were applicable to all the constituent parts of the system, locomotive power, rolling stock, permanent way and civil engineering works, and signalling and control

methods. In the early years of the railways the pressures of new work and the responsibilities of maintaining existing services clearly retarded theoretical consideration and development of the subject.

It is not the purpose of this study to examine the undoubtedly complex interacting issues of the emerging railway system, nor even the growing awareness and response of contemporary engineers to the causes of unsteady motion of locomotives. Neglecting those attributable to the track itself, and these were several, including form, inclination, foundation, sleepers, chairs, rail-joints, subsidence, and deviation from gauge there were others, equally numerous, inherent in the locomotive itself.

3a. Steam Pressure Reaction

The source of instability in the moving locomotive presented engineers with a complex challenge. Before a solution could be devised the problem itself had to be identified and this task was neither quickly accomplished nor was it a clear-cut issue.

During the 1830s one theory attributed unsteadiness to the action of the steam pressure. An idea which gained currency, no doubt, from the erratic behaviour of several of the early types of outside-cylinder locomotive with a short wheel-base. Their short connecting-rods accentuated the vertical components of the force transmitted and, because the alternating upward and downward thrusts of the cross-heads against the slide-bars occurred on each side of the vehicle at the equivalent

of 90-degree crank angles, augmented the tendency of the locomotive to rock. As wheel-bases increased in length, as they did almost from the beginning because the growth in power made greater weights inevitable which in turn necessitated six-wheeled engines, so too, connecting-rods were lengthened with a consequent reduction in their operational obliquity and an improvement in the dynamical performance of the locomotive. Resulting from this trend the theory was eventually discarded. Although, of course, slide-bar reaction remained one of the disturbing forces on a locomotive, but one of diminished significance. Essentially, the general idea of unsteadiness due to steam-pressure reaction was one of the 1830s and by the following decade it was no longer seriously maintained. Even so, the topic was still subject to some discussion and Robert Stephenson obviously considered it worthwhile to inform the Gauge Commission that he did not believe that steam pressure contributed to irregular motion.[15]

By the artifice of a little pyrotechnical demonstration George Heaton confirmed this view. He bored a small hole in the middle of a gun barrel and placed two pieces of iron, fitting the bore of the barrel, each weighing 20oz up to each side of the hole and then put a few grains of gunpowder between them. The barrel was placed on a bed of sand so that any movement would be marked. Upon firing the gunpowder, the pieces of iron were blown the same distance as each other from the hole, while the barrel remained unmoved.[16] Thus Heaton showed that the explosive force of the gunpowder, representing the effects of steam pressure, on the two pieces of iron, simulating the

cylinder-head and the piston respectively, was equal and opposite and had no disturbing effect on the gun barrel representing, in his experiment, the locomotive frame. He repeated the experiment several times. On some occasions he merely substituted pieces of iron of a different weight; in other tests he made the two pieces of metal, representing cylinder-head and piston, unequal in weight. In these latter cases, upon detonation, the two were blown unequal distances. But in every instance the barrel remained stationary. It was not, of course, a strictly valid test because the iron mass representing the piston had no kinetic relationship with the gun barrel whilst on the locomotive, as mentioned above, the piston was directly connected to the frame via the connecting-rod and slide-bars. Nevertheless, this series of experiments provides further evidence that George Heaton was an engineer fully cognisant of current technical problems and also prepared, by means of experimental investigations, to examine them in a methodical way. In this he appears to have been outside the general run of railway engineers. Whereas they almost certainly lacked the time and inclination for such activities he, unlike them, was a proprietor of his own business and with obvious technical interests he also possessed sufficient leisure, resources and facilities for conducting such tests. Despite early indications that valuable results could be obtained from experimental work, remarkably little of it appears to have been performed by Railway Companies and it was not until the final years of the nineteenth century, when locomotive testing stations were established in both Russia and the United States

of America, that the opportunities thus afforded were recognised and taken somewhat more seriously. This trend which accords with the craft origins and development of locomotive engineering was in marked contrast with, for example, electrical engineering and chemical technology[17] which were both born and nurtured in a laboratory environment.

3b. Height of the Centre of Gravity

Another misconception of the early railway engineers, which persisted for many years and led to some abnormal designs, concerned the height of the centre of gravity. A low centre of gravity was deemed of importance in the beginning partly from general ignorance of the locomotive as a vehicle, but also from fear of over-turning or derailing on the very poor tracks of the time. (Fishplates, for example, were not used before 1849-50 and many sections of main line still retained the original stoneblock sleepers until 1852-53).

The main advocate of a low centre of gravity appears to have been T.R. Crampton although the extreme manifestation of this theory in Great Britain occurred in Francis Trevithick's 'Cornwall', see Fig.2.1, built at Crewe in 1847. The design necessitated a complicated boiler placed beneath the driving axle. A divided boiler with the driving axle located between the two sections was proposed by Zerah Colburn in 1854, Fig.2.2, while the following year MM. Blavier and Larpent's 'L'Aigle', Fig.2.3, was built in France. It was taken as axiomatic by the Gauge Commission that the centre of gravity of the locomotive should be kept low and as the preceding examples from the United

States and France reveal that idea was seriously entertained among locomotive engineers in other countries too until at least the middle of the nineteenth century. In actual fact the higher the centre of gravity the better the locomotive behaved with respect to riding since the resultant lateral forces and hunting at the flanges were diminished. Indeed, if normal speed restrictions on curves were complied with it was impossible to get a centre of gravity that was high enough to be dangerous. G.P. Bidder showed the height of the centre of gravity to be of no practical consequence when he told the Commissioners that with a centre of gravity 5ft above rail level and rounding a curve of half-a-mile radius a narrow gauge carriage could theoretically travel at 130 mph before overturning while a broad gauge vehicle would probably require a speed of 150-160 mph. Not unrealistically he added that such speeds were hardly likely to be either attainable or required.[18]

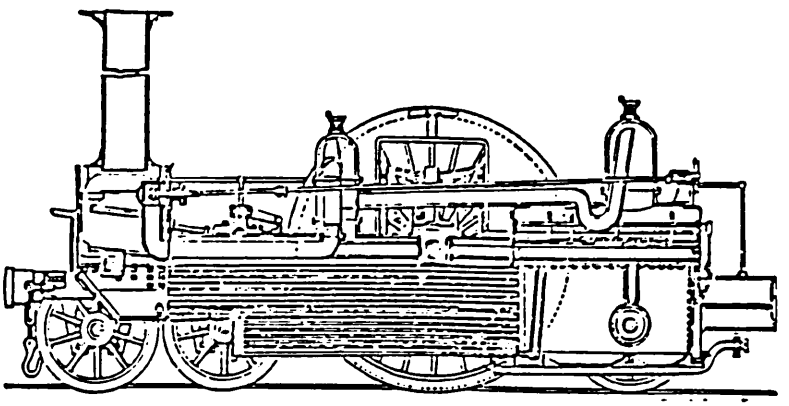


Fig.2.1 Trevithick's 'Cornwall', 1847

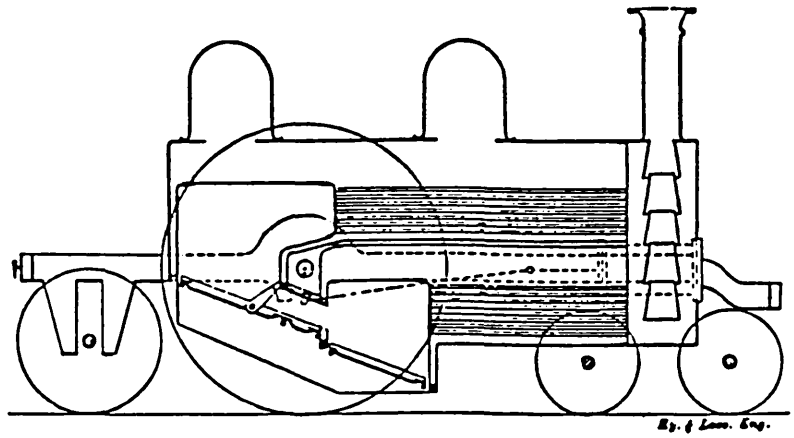


Fig.2.2 Colburn's Design of Locomotive Double Boilers, with Driving Axle Between

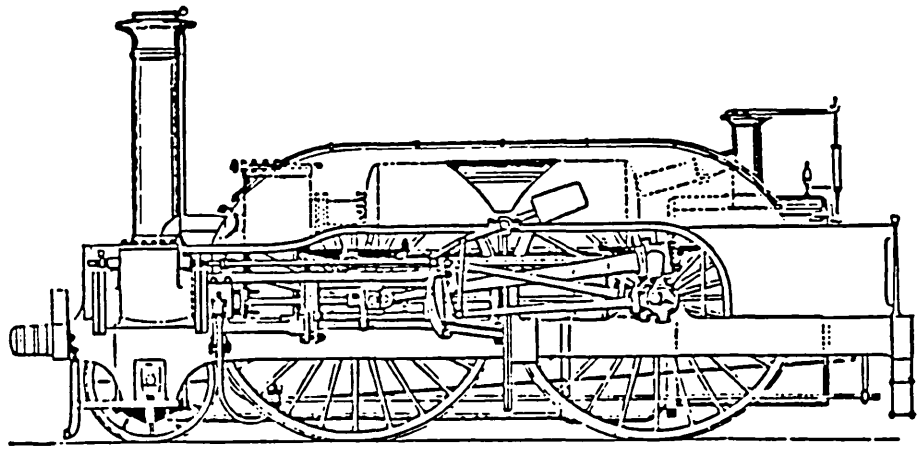


Fig.2.3 MM. Blavier and Larpent's Engine, 'L'Aigle', 1855

These three drawings are reproduced from Development of the Locomotive Engine by Angus Sinclair. Angus Sinclair Publishing Co., New York, 1907.

This notion about the centre of gravity was only gradually discounted. John Gray thought that it was a matter of little consequence, a view shared by J.E. McConnell, but other engineers among whom can be counted Joseph Locke, William Cubitt, Daniel Gooch and William Fernihough were all of the opinion that it should be kept low. The fallacy of the low

centre of gravity could easily have been appreciated from the usual triangular form of diagram, and Daniel Gooch provided such a diagram[19] to the Gauge Commission in claiming superiority for the broad gauge. However, it must be remembered in assessing such claims that the argument is founded on the assumption that the base line is rigid and not liable to spreading or sinking. Experience on railways during the 1830s and 1840s showed that these very failings were not uncommon.

Theoretical considerations were clearly of little influence against the opinion of the prominent engineers and it seems not unreasonable to conjecture that the three locomotive designs referred to, and illustrated above, all originated from the authoritative recommendation of the Gauge Commission. Of the two engines built neither was successful. When, eventually, this idea was gradually abandoned it was in the light of practical experience rather than as a result of scientific analysis.

3c. Coned Wheels

The early short wheel-base engines, especially those with overhanging masses, e.g. outside cylinders at the front end were prone to oscillatory motion, this tendency was promoted by the use of coned wheel treads which gave the vehicle a natural sinuous motion. W.J.M. Rankine was an early advocate of cylindrical rather than conical wheel treads for locomotives and carriages not only on account of reducing power loss and the inevitable acceleration of wear of track and rolling stock, due to the lateral shocks as wheel flanges periodically ground along

the track, but also because he deemed them safer.

> Saving in power by using cylindrical wheels is a minor advantage, in comparison with their superiority over conical wheels in point of safety. It is well known that locomotive engines moving at a high speed are liable to be thrown off the rails by trifling obstacles; and, indeed, that they sometimes leap off spontaneously, without having met with any obstacle that can be detected. This evidently arises from the circumstance, that a carriage, and especially a locomotive engine, with conical wheels, never moves straight forward but for an instant at a time; so that whenever a small accidental obstruction, or an increase of speed beyond a certain limit, causes it to leap higher than the depth of the flanges, it is almost certain to alight off the track.
>
> This source of danger, which has been the cause of many accidents, is entirely removed by the use of cylindrical wheels.[20]

Although the experiments on which Rankine's paper is based were carried out on the Edinburgh and Dalkeith Railway, a horse-worked line, tests were conducted with elevated outer rails when a branch line was constructed to the harbour of Leith in 1837, and the cylindrical wheels negotiated curves smoothly, at 10-12 mph without 'flange grinding'. Nevertheless he clearly regarded the system as applicable to high-speed locomotive

working.

The practice of coning wheel tyres for the twofold purpose of reducing the abrasion of the flanges on the rails and to facilitate the motion of wagons round curves was noted on the Stockton and Darlington Railway during 1826-27.[21] Certainly it was well-established before the introduction of high operating speeds brought to the fore the dynamic consequences of this design feature. The taper of 1 in 20 on tyre treads, referred to by D.K. Clark[22] in 1856, remained the norm in Great Britain thereafter, although to reduce the concomitant sinusoidal motion and to increase passenger comfort on express trains it was sometimes reduced to 1 in 100. However the improvement secured was temporary because wear resulted in a deterioration of riding quality to the extent that there was little discernible difference from tyres originally coned at 1 in 20.[23] The evidence suggests that this topic has continuously received the attention of engineers, and over the years a variety of tapers have been tried with practice in America being significantly different from that in Europe.[24]

The use of high-speed cine-cameras used to investigate wheel-lift, mentioned in Chapter 7, was also applied to the study of the lateral oscillations of railway coach wheels.[25] Indeed, towards the middle of the twentieth century, with the aid of the latest photographic technology the motion of railway vehicle wheels received greater detailed examination than had previously been undertaken, or for that matter, had hitherto even been possible.

4. The Problem Identified

When writing the words, quoted above, about locomotives travelling at high speeds spontaneously leaping off the rails Rankine did not refer to the presence of other disturbing effects either separately or in combination with the sinuous motion generated by coned wheels. Furthermore there was no hint that the relationship between speed and the operational stability of the locomotive could be or, indeed, should be the subject of experimental enquiry.

This is also true of, for example, the reports of the inspecting officer for railways. Clearly, at this period, which extended until the mid-1840s, there was no serious suggestion that the source of the trouble was amenable to systematic investigation. If the locomotive ran unsteadily at high speed the remedy was speed reduction. "Why does the machine become unsteady at increased speeds?" was a question which never appears to have been articulated.

However, by 1845, when the work of the Gauge Commission examined many aspects of the railway system major contributory factors to unsteady locomotive motion were identified. One of them was, of course, excessive speed and when the Commissioners' Report was published the following year it included the following observation on the topic.

> ...it is the stability of the road and not the power of the engine that will prescribe the limits of safe speed. ...accidents arising from engines running off the rails...have been more numerous within the last seven

> months than within the preceding five years, and it is questionable whether this contest for speed ought to be carried to any greater length.[26]

Safety was obviously a necessary and major concern of the growing railway system and the Report itself enumerated details of six accidents, taken from the Reports of the Railway Department of the Board of Trade, which occurred between June and December 1845. In these "...the Engine and Carriages or some part of the Train have run off the Line, without any known obstruction..."[27]

Public anxiety was aroused and was mounting, too, and there was an unmistakable demand for action which coincided with the period during which the Gauge Commission sat. The Times urged

> It is high time there should be an end to the dangers on Railways, and the abuses practised by Railway Companies. Scarce a day passes without swelling the list of accidents, and if we were to publish all the complaints we receive on this subject, there would be very little room left in our columns for any other.[28]

Attitudes to public safety, and the responsibilities of engineers and company officials to such matters are not the purpose of this study although it must be noted, in passing, that much of the criticism was undoubtedly exaggerated and unjustified. In his paper[29] on railway accidents given to the

Institution of Civil Engineers in 1852, Captain Mark Huish, while not making any excuses for the failings of railway companies nevertheless attempted to maintain a sense of proportion and to keep matters in perspective with his statement that the railway system was incomparably safer than any earlier transport system. As he pointed out, the publication of Government statistics on railway accidents directed public attention to this topic in a way which did not occur in respect to casualties in steam-boat accidents, deaths in mining, or even the pedestrian casualties of horse traffic accidents (which probably exceeded railway accident victims). Of course, much the same situation still obtains. A railway accident involving a single passenger fatality will receive national newspaper coverage, while the deaths from road accidents, which on average exceed one hundred per week, are generally unmentioned.

Public alarm, warranted or not, did focus the attention of engineers on the matter of safety with a consequent concern for the stability of the vehicle when running at speed. In the issue of The Times quoted above, a brief report was given on the recent accident on the Norfolk Railway where the locomotive after acquiring an oscillatory motion left the rails. In its Editorial the paper stated that the first step was to ascertain the cause of all the accidents and then claimed that in almost every case the reason was mismanagement. Technical reasons, in the sense of the dynamic effects of high speed, were not mentioned and probably were not perceived. It was easier to apportion blame to directors or to drivers driving at excessive speeds to maintain time schedules.

Uncertainty and doubt, however, did not afflict Dr J.B. Melson and in a forthright letter to the Editor of the Iron Times,[30] published on 25 August 1845 he asserted that "the continual recurrence of a particular type of accident and the consequent mortality demanded a public inquiry. The mystery supposed by all to surround the matter should long since have been stripped away and the gratitude of the community given to George Heaton."

Referring to newspaper accounts of the accidents which occurred on the Eastern Counties Railway during June and August 1839, and on the London and Brighton Railway in October 1841, Melson said that the same features characterised these calamities. These were, in order of sequence, high speed, an oscillation progressively increasing in violence, a jumping or jerking motion and a final leap of the engine from the rails. With undoubted exaggeration he claimed that the rails were perfect before the accident although afterwards, he more realistically commented, "...the indications of lateral pressure were clear and unquestionable". Then to the crux of the issue. Unequivocally he attributed the cause of the accidents to neglect of proper attention to the accurate balancing of all the rotating parts, those of the locomotive itself, its tender and the carriages. His argument was illustrated by the quotation of some relevant figures. The cranks and connecting-rods were generally 180 pounds out-of-balance and when the train was travelling at a speed of only 30 mph they had to turn at 180-200 rpm. Situated at right-angles to each other and at some distance from the axis of the engine they were the obvious cause

of instability. In this action they were assisted by the lack of balance in the wheels which, he claimed, were often many pounds heavier on one side than the other.

The mechanism of disaster was then detailed in a penetrating analysis which, incidentally, provides an interesting early description of resonance.

> ...at a high speed the springs are acted upon by the unevenness or swinging of the cranks, connecting rods, etc. until at length, the springs and cranks keep time with each other, when the jumping motion commences, and at every stroke of the engine is increased to a great extent; when, if the speed cannot be immediately and seriously altered, which, with a heavy train is found to be impossible, the engine, in spite of all other efforts to prevent it, jumps off the rails.

An appreciation of the dynamic effects of the machinery of the locomotive on its steady motion is manifest here. From his description, Dr Melson clearly saw that the laws of mechanics could be used to analyse the nature of the problem and presumably from the magnitudes quoted he could have quantified the disturbing forces generated by the unbalanced rotating masses of the locomotive. Likewise, his observation on the effects of synchronisation of the cranks and springs in amplifying the vibratory motion, many years before the emergence of mechanical vibration theory, was an early and unrecognised indication of the potential role of 'mechanics' in understanding

the locomotive. About eighty years later the investigations of the Bridge Stress Committee, discussed in Chapter 6, clearly revealed the magnification of hammer-blow effects due to resonance.

In his letter Dr Melson had warned that until attention was paid "...to this utterly disregarded but important element in the construction of railway machinery..." the public had no safeguard against the continuance of the type of accident in question. It could well be that his motive in writing the letter at that particular moment was to draw the attention of the Gauge Commissioners to the topic. The Gauge Commission had started taking evidence on 6 August 1845.

5. The Gauge Commission and its Report

Appointed to consider matters relating to the inconveniences caused by the co-existence of different gauges, the means of overcoming or mitigating them and the desirability of having a uniform gauge throughout the country, and associated issues, the Commissioners were: Lieut.Col. J.M.F. Smith, R.E., former Inspector General of Railways, G.B. Airey, Royal Astronomer and P. Barlow, Professor of Mathematics, Royal Military Academy, Woolwich.

In the course of their enquiries which involved the examination of forty-eight witnesses over a period of several months, extending from 6 August to 18 December 1845, many matters pertaining to the railway system and its functioning were considered. The witnesses included carriers, chairmen, contractors, directors, managers, secretaries and military

personnel as well as engineers, engine builders and locomotive superintendents. Every major railway company in England was represented. The topics examined ranged from the inconvenience caused to passengers at points of break of gauge, to the transport of goods and livestock, strategic matters involving troop movements, and technical points concerned with the design, construction and running of locomotives and rolling stock plus matters on the permanent way.

Six thousand five hundred and thirty-five questions and answers are incorporated in the Commissioners' Report, which together with its Appendix containing supplementary replies to questions, statistical returns and 'An Account of Experiments Made Under the Sanction of the Commissioners' amounts to a document of eight hundred and eighteen pages. Quite apart from its significance at the time, and it led to legislation requiring all future construction to be on the narrow gauge, the Report is now of immense value to the historian since it provides an official record of the railway system as it was in the mid-1840s and additionally it contains the views of those engaged in railway affairs.

Locomotive stability was a matter that loomed large in the business of the Commission and in the answers to questions we have the opinions of the major engineers of the period on a variety of technical issues. Resulting from these lengthy deliberations the Report singled out as the primary causes of derailments, excessive speed, defective track, bad rail-joints and badly balanced engines.[31] Thus by 1845 the problem had been unmistakably identified and publicly acknowledged and through the

evidence of William Fernihough the beginnings of a 'theory of balancing' had been established. This is discussed in Chapter 3. Of the man we know no more than he, himself, told the Gauge Commissioners, that is, having worked at Forrester's in Liverpool he had been with Edward Bury for something over two years and at the time of giving evidence to the Commission he was the Locomotive Superintendent of the Eastern Counties Railway, an appointment (his first with a railway company) that he had held for two years. William Fernihough thus remains a shadowy figure who emerged, seemingly from nowhere, fleetingly appeared before the Gauge Commissioners for a day towards the end of October 1845 and thereafter disappeared into oblivion.[32] The content and quality of his answers indicate that he was a knowledgeable and competent engineer, technically the peer of any of the more eminent railway engineers to give evidence, and yet of his life and work our only source of knowledge is his replies to the questions of the Commissioners.

Notwithstanding the complete lack of biographical detail it cannot be doubted that in the history of locomotive balancing Fernihough must occupy a pre-eminent position because his expedient of compensating the inertia forces of the reciprocating components by rim weights in the driving wheels became and remained the general method of meeting this requirement. How he was led to the problem and its solution remains a matter of surmise. Possibly it was an awareness of the mounting seriousness of unsteady running or perhaps may be an interest awakened or stimulated by the letter of T.R. Crampton to The Railway Times in which he attributed the

oscillation in locomotives to unbalanced reciprocating masses.[35] Perhaps, even more pertinently, since he had been employed by George Forrester, it was familiarity with that Company's 2-2-0 locomotives built for the Dublin and Kingstown Railway in 1834. These engines, the first built with horizontal outside cylinders had a very short wheelbase and displayed a violent swaying motion at speed, a characteristic which earned them the nickname 'boxers'. Steadiness was improved a couple of years later by adding another pair of wheels to lengthen the wheelbase. Thus direct experience of troublesome locomotives could have attracted the attention of Fernihough to the problem of unsteady motion. Whether or not this originated with Forrester's locomotives is open to question but his familiarity with the issue on the Eastern Counties Railway is attested in his evidence to the Gauge Commission.

According to C.J. Allen the first passenger engines built by Braithwaite Milner & Co. for the Eastern Counties Railway in 1839 were notorious for unsteady running.[34] The day after the formal opening of this railway a derailment killed both the locomotive driver and fireman while a year later another accident claimed the lives of the engine crew and one passenger. It does not seem unreasonable to conjecture, then, that William Fernihough had had direct and convincing experience of the consequences of unsteady running and was, on the Eastern Counties Railway confronted with a major problem that demanded immediate and effective action. There was no doubt in his mind; the main cause of unsteadiness was sinuous motion.[35] His opinion was not based merely upon theory, although he was

capable of theorising, nor on the views of his contemporaries, but on the incontrovertible evidence of his own senses. His knowledge was derived from personal acquaintance with his own locomotives and he told the Commissioners that he always travelled on the footplate and knew the state of his engines better than his own foreman.[36] Quite probably this personal experience and his practical solution to the problem by adding rim weights convinced him that his answer was the correct one. In the sense that it provided a simple solution, relatively cheap and easily incorporated into the locomotive, despite the fact that it introduced the 'hammer-blow' effect to the rails, it was a satisfactory method of dealing with the instability of the machine. Although a compromise which eventually led to significant difficulties it solved the immediate trouble and since during the 1840s the most pressing issue was improvement of the dynamic behaviour of the railway engine, it proved to be an acceptable compromise. In this it cannot be regarded as anything extraordinary. Compromise is the very essence of engineering and the value of Fernihough's compromise was that, knowledgeably and competently applied, it was capable of meeting the balancing requirements of the steam locomotive over a century after he had announced his method to the Gauge Commission. However, this is a conclusion drawn with hindsight and it is by no means certain to what extent the rim balance weight was regarded as a compromise by Fernihough. He clearly recognised the generation of vertical forces but confidently discounted any consequent adverse effects from them and insofar as his method gave a 'perfectly steady' engine, it might be

argued that he regarded his method not as a compromise but as a definitive solution. But the more detailed analysis of the evidence presented in the following chapter will reveal that opinions on this matter differed among contemporary engineers and the compromise nature of the method was certainly perceived and the fact that it could create a bigger problem than the one it solved was acknowledged.

Reference has been made, above, to the improvement in behaviour in Forrester's 'boxers' secured by adding a further pair of wheels, converting them from 2-2-0s to 2-2-2s. This, in fact, was the expedient adopted by a number of engineers. Since the steadiness of locomotives was enhanced by increasing the number of wheels some of the accidents, mentioned earlier, led to a vociferous and growing demand for the use of six-wheeled engines. Major General C.W. Pasley concurred with this and in answering the final question of the Gauge Commissioners he voiced the opinion that not only all locomotives but their tenders, too, should have six wheels and the tenders, he emphasised, ought to have powerful brakes capable of acting on all six wheels simultaneously.[37]

As a point of reflection on the design philosophy of the locomotive engineers during the 1830s and 1840s, and in particular in their appreciation of the hazards associated with the momentum of heavy trains moving at high speeds, it is interesting to note that in their efforts to obtain more power and higher speeds from their engines they did not regard the development and incorporation of an efficient braking system as a necessary concomitant.

Undoubtedly contemporary evidence clearly reveals that the need to improve the stability of locomotives and considerations of passenger comfort gave impetus to the move towards six-wheeled engines[38] and the practice of stiffly coupling tenders to their locomotives. This trend reached its climax, perhaps, with Bidder's advice to the London and Birmingham Railway Co. that Stephenson 'A' type locomotives should be connected to the tender by a screw coupling to secure "almost a 12-wheeled machine". Whilst admitting that the arrangement increased the resistance in negotiating curves he claimed that it gave "great steadiness and security to the engine."[39]

Additionally, and in similar vein, the railway companies took other precautions in the attempt to isolate their passengers from the worst effects of the erratic motion of the locomotives. Not that this earned them universal gratitude. Dr Melson, for example, scathingly rebuked them for

> ...the miserable expediencey of inserting empty trucks and luggage vans between the engines and passengers, with a view of making the thumping of the public a little less severe.[40]

In a more restrained manner Edward Bury admitted use of the same artifice when he told the Gauge Commission

> When we have taken any part of the royal family, we have always put more carriages on the train than we wanted for the accommodation of the passengers, in order to have the engine steadier.[41]

Such pragmatic responses, although productive of the immediately desired result were not conducive to a permanent solution of the problem and their adoption suggests that the engineers responsible were ignorant of the real causes. However, as this chapter has shown, others were more knowledgeable. George Heaton, for example, had indicated that the tendency to rocking and jumping existed in the six-wheeled, as in the four-wheeled, locomotives and from this aspect they were no safer.[42]

Of the theories for the irregular motion of locomotives two of them, those of steam pressure reaction and the requirement for a low centre of gravity were erroneous and misleading. The former had been discarded by the time of the Gauge Commission and the latter, probably as a result of the Commission's advocacy, led to a few designs - briefly described earlier in this chapter - specifically aimed at securing this condition. However, these locomotives were not satisfactory and the height of the centre of gravity above the track gradually ceased to be an issue of concern.

Balancing, on the other hand, was established as an important parameter of locomotive design and remained so thereafter. Indeed, so far as the locomotive is concerned this is unquestionably the most significant outcome of the Gauge

Commission for in no other aspect did its deliberations lead to advantageous innovations or modify the slow, natural growth of the machine in size and power. Before taking up the story of balancing again, in Chapter 3, some consideration must be given to the subject of priority in the use of balance weights in the wheels of locomotives.

6. The early use of balance weights in locomotives

The proper credit for priority is an important and an inevitable problem for the historian of technology and particularly so when dealing with the railway locomotive. Its development is characterised by a number of valuable improvements and while it is, perhaps, natural to ask who invented a particular device it is not possible to provide a definite answer. Uncertainty prevails on many points and this situation seems likely to persist. Nevertheless if questions of priority cannot be answered with any certainty they cannot be entirely avoided either.

If some inventions were the outcome of inspiration or intuition others appear to have been the result of experience, observation and operating difficulties and such appears to be the case with locomotive balancing.

By 1845, despite Dr Melson's assertions (see Section 4) the balancing of locomotives - although not generally practised - was not utterly disregarded. Indeed, by that time, claims and counter-claims to priority of invention were already six years old.

In a letter to the Mechanics Magazine of April 1839,[43]

George Heaton claimed to have introduced crank balances[44] in 1838 but this was challenged by Mr Richard Evans of Manchester, the following month, who wrote that all engines built by Messrs Sharp, Roberts & Co., since December 1838, were fitted with such balances.[45] And, he added, Sharp, Roberts made no claim for the originality of the device since they had previously seen it applied to a locomotive on the London and Southampton Railway and credited its invention or application to Mr Dawson of that line. However, while Dawson is stated to have filled the space between two spokes of the wheel in the form of a panel as a counterpoise, Roberts achieved the same result, more economically, by the use of a rim weight.

Pursuing the matter in the June (1839) issue of the same journal[46] Heaton invited Evans to visit 'Mr Dockry' (R.B. Dockray), the Resident Engineer of the London and Birmingham Railway, who would show him a model of a crankshaft and two wheels with the balance weights placed exactly as Evans had described them to be on Sharp, Roberts engines. The model had been in Dockray's possession since the beginning of October 1838, having been made during August or September at the request of one of the directors of the London and Birmingham line. Its purpose was to demonstrate Heaton's claim that balance weights would not only prevent the rocking of engines but would also effect a saving of power.

Presumably these model tests were convincing because the directors ordered the 'Brockhall',[47] one of the Company's locomotives at that time undergoing repairs at the Vulcan Iron Foundry, Birmingham, to have balance weights fitted to it

according to Heaton's plan and under his supervision. As a result of these modifications it was reported that the locomotive exerted one uniform steady pull at its work, the side sway disappeared, while the engine ran equally steady whether it made 6 or 160 strokes per minute. After running like this for seven weeks during which time the machine acquired the reputation of being a very steady engine the balance weights were removed, after which it displayed the same snatching and swinging motion that was common to all locomotive engines of the usual construction, that is, with unbalanced revolving masses. In this condition Heaton found that the engine when running at 22 mph, or faster, would advance and recede from the tender from three-quarters of an inch to one inch every stroke of the engine.

The correspondence on the priority of balancing the revolving masses of locomotives, in the Mechanics Magazine, did not go beyond Heaton's second letter in which having stated that he entertained no fear of being forestalled in the invention he modestly and summarily brought the matter to an end by expressing his satisfaction at being instrumental in the adoption of so useful an invention.

Early in 1880, in the pages of The Engineer[48] the subject of priority was raised again, when the three letters to Mechanics Magazine of 1839 were reprinted. The writer of the article in The Engineer thought that Heaton's second letter was conclusive, in Heaton's favour, since it elicited no reply.

Much earlier than this, however, during June 1848, in the discussion following the reading of J.E. McConnell's paper[49]

at the Institution of Mechanical Engineers the issue was referred to but in such terms that any real conclusions can hardly be drawn from this evidence, apart from the important point for the historian, that engineers speaking from memory are frequently inaccurate. A contributor, Mr Middleton, acknowledged George Heaton to be the originator of the system and claimed to have been associated with him in having it tried on the London and Birmingham Line, where it was first introduced in 1839, and on other railways. But, he reported, that they had met 'with great discouragement'.[50] McConnell himself was less certain of the origins of the method. He told the audience that it had been introduced to him by Heaton six years earlier and that he had adopted it on the Birmingham and Gloucester Railway which he believed was one of the first instances of its implementation.

According to Mr Cowper, another participant, when he visited Birmingham and learned of Heaton's scheme he discovered that it was identical to that used by Messrs Braithwaite and Milner to balance wheels on the Eastern Counties Railway eleven years previously[51] (i.e. 1837). In making this statement he appears to have initiated an error destined to be repeated more times than was excusable and indeed by no less an authority on locomotive history than E.L. Ahrons in his major work on the subject, The British Steam Locomotive 1825-1925.[52]

The first four locomotives for the Eastern Counties Railway, 0-4-0s reputed to be of the 'Bury' type, were not built by Braithwaite, Milner & Co. until 1838 and the first engines did not run on this railway until the following year when, from

the beginning, as referred to above, derailments occurred. Probably these accidents focused the attention of the engineers on the problem of instability and the necessity of neutralising unbalanced forces.

In attempting to assess these claims and counter-claims it must be borne in mind that in the late 1830s and the early 1840s identical difficulties were being experienced by railway engineers throughout the country and it is not surprising that more than one locomotive superintendent should arrive at the same solution. By that time the effects of rotary unbalance had clearly manifested themselves. Recalling that Dawson,[53] on the London and Southampton line, had been acknowledged by Sharp, Roberts to have preceded themselves in the use of counter-weights in the wheels and that at the same period George Heaton's ideas were being tried by McConnell, while Thomas Hunt on the North Union Railway and John Braithwaite on the Eastern Counties Railway were adding counter-weights either to crank bosses or wheel rims, the evidence leads to the conclusion that their adoption occurred on a few railways, independently and contemporaneously to solve a common problem.

It was not until 1937 that the anonymous author of an article 'A Century of Balancing'[54] drew attention to the mistaken claim of wheel balancing on the Eastern Counties Railway a hundred years earlier. In correcting this error the author inexcusably perpetrated another with his statement that Thomas Rogers, founder of the Rogers Locomotive Works, had in the United States during 1837 patented the application of weights opposite the cranks to balance the revolving parts.[55]

Whether Rogers actually applied for a patent is not clear but American patent records reveal that one was not granted. Nor is it likely that he could have hoped to patent such a basic principle for the idea of counter-balancing was hardly a new one. Some of Richard Trevithick's earliest engines pre-dating Roger's alleged patent by about thirty years possess large flywheels with very obvious counterweights for the same purpose.

A piece of evidence, from the United States, shows that a balance weight was incorporated in the driving wheel of a locomotive as early as 1830.

James Renwick, Professor of Natural Experimental Philosophy and Chemistry, in Columbia College, New York, published in that city during 1830 a small book entitled Treatise on the Steam Engine[56] which contained an engraving of the newly imported 'Stourbridge Lion' (see Fig.2.4). This drawing shows the locomotive fitted with rim counterweights opposite the crank on the rear driving wheels. Clearly, for a slow-speed engine at this very early date, the counterweight was included to effectively give static balance to the heavy rocking beam rather than from any consideration of dynamic balance which only really became significant at much higher running speeds. What is of particular interest and importance for the history of locomotive balancing in Great Britain is that this locomotive had a sister engine, the Agenoria, built at the same time and probably carrying similar balance weights. It was built for the Earl of Dudley's Colliery Railway and, according to Ahrons,[57] worked for about thirty years during which time it was modified in several important respects including the fitting of new cast

iron wheels which also incorporated balance weights in the rear driving wheels, although it is not clear when Agenoria acquired them. The locomotive is now preserved in the National Railway Museum at York. On the basis of this evidence it seems likely that 'Agenoria' was the first locomotive to run in Britain with balance weights in the wheels and quite possibly some engineers observed, and appreciated that if a revolving balance weight could compensate the motion of the overhead beam it could fulfil a similar duty for the crank and its appendages.

Before leaving 'Stourbridge Lion' it is worth noting one or two other points since they highlight the problems confronting the historian. Renwick did not name the engine he illustrated but merely stated that it was made under the direction of Mr Horatio Allen for the Delaware and Hudson Rail-Road Co. at Stourbridge, in England. The engraving depicts the engine devoid of a nameplate, although later versions of the drawing based on the Renwick illustration, for example that shown by Ahrons,[58] prominently feature the name 'Stourbridge Lion' on the side of the boiler. We cannot be certain of its original name. In his Newcomen Society paper 'The Four Locomotives imported into America in 1829 by the Delaware & Hudson Company'[59] L.F. Loree quotes a letter written by John B. Jervis during August 1829 which refers to it simply as the 'Lion'. Thus, although we confidently speak and write of 'Stourbridge Lion' as, indeed, many books have described and illustrated it there is no contemporary evidence that this was its official designation and possibly 'Stourbridge' was

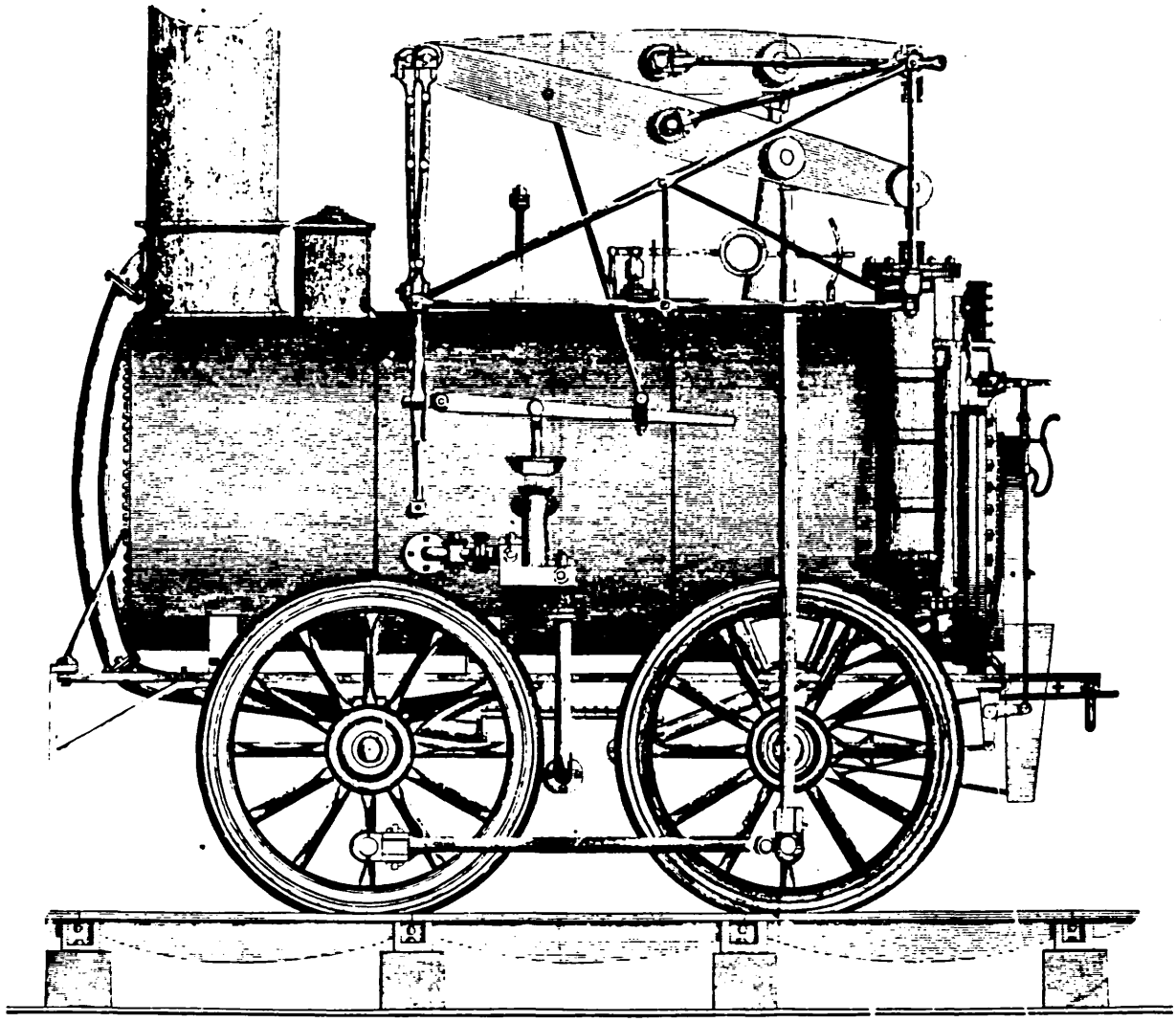


Fig.2.4 Engraving of the 'Stourbridge Lion'
prepared by James Renwick from the original locomotive

subsequently bestowed on the locomotive to distinguish it from other 'Lions'.

In 1932 the Delaware and Hudson Railroad built a full-scale replica of this famous locomotive but omitted the counterbalance weights from the driving wheels. The exclusion of what must have been one of the most remarkable features of the engine is incredible and if, as seems almost certain, the work was based on the Renwick engraving, it was also deliberate. Of course, it could be contended that the illustration is ambiguous and the wheels do not carry balance weights but in questioning the acceptability of this interpretation with the Smithsonian Institution, the opinion of John H. White,[60] the American railway historian, is that the drawing is indisputable. Indeed, on this topic his appraisal of the locomotive is "Possibly the most interesting feature of the wheels, if not of the entire engine, is the counterweighting of the rear drivers."[61]

Likewise, the Wayne County Historical Society,[62] Honesdale, Pennsylvania confirm that in their view the Renwick drawing is correct which must, by any reasonable assessment, be accepted by the historian since it is the only authentic contemporary drawing of the engine. Why then was this significant innovation omitted from the reconstruction? It is improbable that the actual reason will ever be discovered and the historian can only speculate. Possibly the engineers responsible for building the replica were aware that technically such balance weights were not necessary and indeed were not used on other locomotives (for example, Hedley's 'Puffing Billy') of

similar design. Furthermore, they probably 'knew' that in 1829, and for many years thereafter, locomotives were not balanced. Therefore the reconstruction was based on their perception of the state of locomotive technology in 1829 rather than an explicit adherence to a particular drawing - and one which they may have regarded as unrepresentative of current practice. In other words they interpreted the past in terms of their own engineering knowledge and practice, that is, primarily as engineers rather than as historians with a meticulous respect for a documentary source.

Having established from what may be considered conclusive evidence that Rastrick was using rim weights on a locomotive engine in 1829 the question arises as to how he acquired the idea. The evidence suggests that it was from Richard Trevithick. An early association obviously existed between Rastrick and Trevithick since in 1808 the former assisted as resident engineer, under Trevithick, on the Thames Driftway. Subsequently Rastrick joined Hazeldine's foundry, eventually entering into partnership as Hazeldine, Rastrick & Co. By 1806 Hazeldine was a large manufacturer of Trevithick engines and he is reputed to have built the 1808 London locomotive.

In his biography of his father, Francis Trevithick quotes a draft of a letter from Richard to Rastrick, dated 7 December 1812, in which he gives the instruction, "Mind to cast a lump, or screw on a balance, of about 1 cwt. on one side of the flywheel."[63]

Thus, about seventeen years before 'Stourbridge Lion' and 'Agenoria' were constructed the attention of Rastrick had

been directed to the matter of counterbalancing and its desirability, if not its necessity. The lesson he learned on stationary, agricultural engines probably struck him as being applicable to a locomotive. Seemingly, therefore, and in a sense by default, priority for the use of balance weights in the driving wheels of a steam locomotive must be accorded to John Rastrick. On balance, the evidence suggests that his two locomotives carried them and yet, so far as the evidence goes, his knowledge and understanding of the real problem was deficient. He appears not to have had any clear comprehension of the elementary laws of mechanics or the nature of the dynamic problems of the locomotive. With his long-standing, if somewhat qualitative and incomplete, appreciation of the need for balancing and in his capacity as a Rainhill Trial judge it might have been expected that he would have made some comment on 'Rocket' which, as mentioned earlier, displayed a marked unsteadiness when running at speed. However, his 'Rainhill' notebook[64] does not even refer to the subject. Even more inexplicable are his views expressed to the Gauge Commissioners on the subject of locomotive oscillation when he declared it impossible for outside cylinders to produce any yawing motion unless there was play in the frame of the engine.[65]

If, on the basis of Renwick's illustration, priority is given to Rastrick it must be conceded that he was not influential in establishing the practice of balancing, indeed his influence on locomotive design was negligible and his excursion into the manufacture of these machines was short-lived.

Of far greater importance than judging the merits of the individual claims discussed so far, all of which were concerned with balancing rotating masses only, is to determine when the beneficial practice was generally accepted into locomotive design and construction. We must also recognise that many of the claims made by the engineers involved were no more than enthusiastic and exaggerated reports based on improvements secured rather than objective analyses of dynamic behaviour. For example, the report that the 'Brockhall', when subjected to Heaton's scheme, produced an even pull free from nosing is just not to be believed. Without some balance for the reciprocating masses this smooth action was simply unattainable. And as this chapter has shown, it was the mid-1840s before Fernihough provided some 'overbalance' to compensate the inertia forces. From this time onwards it is possible that locomotives could have been reasonably well balanced and steady running but, again, as the following pages will show the evidence suggests that the majority were not. Over ten years after Fernihough had divulged his method, D.K. Clark reported that "the locomotive stock of this country is very imperfectly balanced".[66]

Quite remarkably, in this paper, Clark claimed for himself the honour of being the first in the country to accomplish a complete balance - in the outside cylinder engines he had designed for the Great North of Scotland Railway, for which Company he was Locomotive Superintendent from 1853-55. Of course, it is not possible to determine with any exactitude what Clark meant by 'complete balance' or why he ranked his achievement over that of Fernihough for example, because since,

like Fernihough, he only used rim counterweights his design did not eliminate vertical forces. Theoretically, and in practice, Bodmer's locomotive of 1844-45 was entitled to the distinction. A trace of hero-worship is also to be detected in his attribution to George Stephenson of defining the condition of making provision for reciprocating masses by balance weights in the wheels. Indeed, in the Introductory Preface to his book Railway Locomotives he goes even further and writes

> ...the superior method of equilibration suggested by Mr Stephenson, propounded by Mr Fernihough, investigated by Nollau and others, and developed in this Work,...[67]

Contemporary evidence indicates that Stephenson's role was far less significant in this matter. As noted above, the use of balance weights on steam engines seems to originate with Richard Trevithick and there is no evidence to indicate that either George Stephenson, or his son Robert, was influenced by the Cornish engineer in this respect. Indeed, although they met briefly in South America, Robert Stephenson and Trevithick did not know each other. Far from being leaders in the technique of balancing locomotives the Stephensons initially appear to have taken little interest in the topic and only somewhat tardily adopted rim balance weights. Major General C.W. Pasley, Inspector of Railways, and the last witness to appear before the Gauge Commission told the Commissioners of the importance, in his opinion, of balancing all the parts of a locomotive engine as much as possible. And he continued by telling them that many

locomotive superintendents shared his views and acted accordingly. Revealingly, he added,

> Some few, amongst whom is Mr Robert Stephenson, have not attached so much importance, or any importance that I am aware of, to this point.[68]

The study of McConnell's paper[69] referred to earlier attests to the prejudice existing in railway companies to the practice of balancing and the author himself stated that Stephenson was a late convert to viewing it favourably. No doubt the subject was forced to his attention by the derailment of one of his locomotives during the Gauge Experiments. Even then his answer to the problem appeared not to be weights in the wheels but a three-cylinder locomotive. This will be considered in greater detail in Chapter 4. Preoccupation with the multifarious problems of railways and railway schemes on a large scale probably prevented Stephenson, and others, from giving the matter the close, detailed attention it merited. But as this chapter has shown the issue had become one of major concern by the mid-1840s. In this trend the role of the Gauge Commission was of vital importance for it dealt extensively with questions of locomotive stability and established balancing as a major consideration in the design of a steady and safe vehicle.

William Fernihough's evidence to the Gauge Commission will be examined in the next chapter which will also deal with the development of the theory of locomotive balancing during the second half of the nineteenth century.

Chapter 2

The Railway Locomotive

References and Notes

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2. Ahrons, E.L., The British Steam Railway Locomotive 1825-1925, The Locomotive Publishing Company Ltd., London, 1927, p.16. The author attributes these details to Edward Woods.

3. Simmons, Jack, The Railway in England and Wales 1830-1914, Vol.1, The System and its Working, Leicester University Press, 1978, p.17.

4. Woods, Nicholas, A Practical Treatise on Rail-roads and Interior Communication in General, First edition, London, 1825, p.290.

5. Marshall, C.F. Dendy, Centenary History of the Liverpool & Manchester Railway, The Locomotive Publishing Company Ltd., London, 1930. This work contains a transcription of John Rastrick's Rainhill Notebook which records that

on Tuesday, 6 October 1829, Stephenson's engine attained 12 mph (p.21) and on Tuesday, 13 October 1829, Hackworth's locomotive averaged 13.87 mph (pp.50-51).

6. Ibid, p.55.

7. Reed, Brian, 150 Years of British Steam Locomotives, David & Charles, Newton Abbot, 1975, p.23.

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10. Public Records Office, Inspectors' Reports, Ref.MT29, vols.1-9 Vol.4 (1845) is missing.

11. Ibid, Ref.MT29/1, pp.352-354.

12. Ibid, Ref.MT29/1, p.352.

13. Ibid, Ref.MT29/1, p.354.

14. Patent No.6616, J.G. Bodmer, 24 May 1834. The work of this engineer on balanced locomotives and engines is considered in greater detail in Chapter 4.

15. Report of the Gauge Commissioners. Presented to both Houses of Parliament by Command of Her Majesty. Printed by T.R. Harrison, London, 1846, Q.247.

16. Unless otherwise indicated all statements referring to George Heaton, the Heaton family, and to Dr J.B. Melson are based on the unreferenced material in the Museum of Science and Industry, Birmingham. See Chapter 1, Note 36.

17. The development and growth of these industries has been characterised by a dependence on a greater theoretical understanding of the appropriate technologies which in turn has been based upon accompanying laboratory experimental activity. This phenomenon has achieved increased significance in many of the important twentieth century technologies including aeronautics, electronics, materials science, petro-chemicals, and radio communication. Their progress is not to be explained in terms of a simple paradigm of evolution and growth such as can be applied to the steam locomotive. With the possible exception of the superheater, introduced into Great Britain in the early years of the present century, locomotive engineering was not characterised by the leaps encountered, for instance, in aeronautical engineering resulting from the introduction of engine supercharging, metal airframe construction and the jet engine or in electrical engineering by the appearance of the thermionic valve, the transistor, the printed circuit and the integrated circuit. However, these parallels, interesting in highlighting the seemingly capricious nature of technological development nevertheless preclude the possibility of explaining the process in terms of a simple model such as 'craft-origin' as opposed to a 'science-based' industry. Although, perhaps, in seeking to sustain the argument of parallels between different technologies it could be contended that in railway terms the diesel-electric

transition provided the equivalent of the jet-engined all-metal aircraft, from many practical, operational aspects such a conclusion is hardly valid. At the most fundamental level the development of aircraft capable of carrying passengers in large numbers depended upon this development whereas this was not the case with railway trains.

On the other hand, the motor-car, indubitably not from the craft stable and despite an immense amount of development work by the automobile manufacturers up to the present day has, nevertheless, remained essentially as it was a century ago.

18. Report of the Gauge Commissioners, Q.4133.

19. Ibid., Q.3493.

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26. Report of the Gauge Commissioners, p.13.

27. Ibid., p.23.

28. The Times, 29 December 1845, p.4.

29. Huish, Mark, 'Railway Accidents; their cause and means of prevention; detailing particularly the various contrivances which are in use, and have been proposed'. Proceedings of the Institution of Civil Engineers, Vol.XI, 1851-52, pp.434-450.

30. Heaton papers. See note 16.

31. Report of the Gauge Commissioners, p.10.

32. In the introduction to his book A Biographical Dictionary of Railway Engineers, John Marshall wrote of the inevitable omission of a number of important engineers because research, extending over seven years, had failed to reveal sufficient information to warrant their inclusion. Fernihough does not even rank among those who he mentioned as being excluded for that reason. Likewise, Cecil J. Allen in The Great Eastern Railway (p.84), having acknowledged that a number of significant ideas in the development of locomotive design had their origin on that railway, failed to name

Fernihough among the Locomotive Superintendents he mentions in the book.

33. Railway Times, Vol.VI, 4 February 1843, p.136.

34. Allen, Cecil J., The Great Eastern Railway, Ian Allan Ltd., London, 1955, p.85.

35. Report of the Gauge Commissioners, Q.4283.

36. Ibid., Q.4286.

37. Ibid., Q.6535.

38. The main reason for increasing the number of wheels on a locomotive was to distribute the weight of the locomotive and this remained so long after arguments about its utility in promoting stability had ceased. Nevertheless, at the period in question, this remedy was seriously advocated and, indeed, implemented. Edward Woods, in his paper 'On certain Forms of Locomotive Engines', Proceedings of the Institution of Civil Engineers, Vol.1, 1838, pp.140-141, stated 'The advantages obtained were almost immediately apparent. The engine lost in a great degree its peculiar rocking motion, as also the unsteadiness arising from lateral undulations; which latter effect was in like manner attributable to the diminution of the angle of which the oscillations were susceptible.'

39. The letter from G.P. Bidder to the Secretary of the London & Birmingham Railway Company, on the conclusion of the gauge experiments is quoted by J.G.H. Warren, op.cit.,p.393.

40. See ref.16.

41. Report of Gauge Commissioners, Q.1216.

42. See ref.16.

43. Mechanics Magazine, 13 April 1839, pp.20-21.

44. The initial method of balancing the crank pin appears to have been by an extension of the centre boss of the wheel diametrically opposite the crank pin.

45. Mechanics Magazine, 25 May 1839, p.117.

46. Ibid., 8 June 1839, pp.164-165.

47. Ibid., 13 April 1839, pp.20-21.

48. The Engineer, 30 January 1880, pp.77-78.

49. McConnell, J.E., 'On the Balancing of Wheels', Proceedings of the Institution of Mechanical Engineers, 13 June 1848, pp.1-9.

50. Ibid., p.9.

51. Ibid., p.9.

52. Ahrons, E.L., op.cit., p.61.

53. Dawson is another railway man of whom we have no biographical details, although according to Brian Reed he was 'running foreman' of the London and Southampton Railway based at the Nine Elms depot.

54. Locomotive Carriage and Wagon Review, 'A Century of Balancing', Vol.XLIII, 14 August 1937, pp.249-251.

55. Ibid., p.249.

56. Renwick, James, Treatise on the Steam Engine, G. & C. & H. Carvill, New York, 1830.

57. Ahrons, E.L., op.cit., p.11.

58. Ibid., p.10.

59. Loree, L.F., 'The Four Locomotives imported into America in 1829 by the Delaware & Hudson Company', Transactions of the Newcomen Society, Vol.IV, 1923-24, pp.64-72.

60. Private correspondence.

61. White, John H., American Locomotives. An Engineering History, 1830-1880, The Johns Hopkins Press, Baltimore, 1968, p.243, where, following the quotation given, the author states that this is the earliest known use of counterweights for locomotives.

62. Private correspondence.

63. Trevithick, Francis, Life of Richard Trevithick, With an Account of His Inventions, E. & F.N. Spon, London, 1872, Vols.I & II. Vol.II, pp.18-21. This letter concerned a threshing engine for Lord de Dunstanville of Tehidy.

64. See ref.5.

65. Report of the Gauge Commissioners, Q.926.

66. Clark, D.K., 'On the Improvement of Railway Locomotive Stock, and the Reduction of the Working Expenses', Proceedings of the Institution of Civil Engineers, Vol.XVI, 1856-57, p.18.

67. Clark, Daniel Kinnear, op.cit., p.VI.

68. Report of the Gauge Commissioners, Q.6531.

69. McConnell, J.E., op.cit.

Chapter 3

BALANCING - THEORY AND PRACTICE

THE SECOND HALF OF THE NINETEENTH CENTURY

At mid-century the theoretical basis of locomotive balancing was enunciated by William Fernihough, in his evidence to the Gauge Commissioners, and also by two Continental engineers, H. Nollau in Germany and Louis Le Chatelier in France. This chapter examines the work of these men, its presentation to the English-speaking world by the writings of D.K. Clark and the ensuing progress, or lack of it, in locomotive practice during the second half of the nineteenth century.

1. The Theory of William Fernihough

On Monday 27 October 1845 W. Fernihough appeared before the Gauge Commission. In his reply to Question No.4294 of the Gauge Commissioners[1] the locomotive superintendent of the Eastern Counties Railway, provides the first evidence of mathematics and mechanics being applied to the analysis of the balancing problem.

Replying to the request for his opinion on Bodmer's locomotive, in which one piston was balanced by the opposite action of a second piston, Fernihough stated that he had seen the locomoitve, at New Cross, but was not disposed to employ the principle on his own railway since it was a complicated way of achieving what the Eastern Counties Railway did 'completely' by more simple means. He did not challenge or question the theoretical correctness of Bodmer's solution to the problem of

balancing the reciprocating masses nor did he comment upon the locomotive's superiority as a track-working vehicle. Its unacceptability, so far as he was concerned, was essentially due to its complex mechanism.

The suspicion and the dislike of 'complexity' in the railway locomotive by the engineers of the 1830s and 1840s, the crucial period during which the 'two cylinder engine with cranks at right-angles' design conclusively established itself as the norm, must be evaluated in the light of prevailing conditions, economic and social, as well as technical. Even at this early stage in its evolution the number of different components in a locomotive was counted in thousands rather than hundreds but the rapidly growing railway industry was confronted with a shortage of skilled labour. At this time nearly all of the processes used in building a locomotive were hand-tool operations and although this predicament gave impetus to the development and adoption of machine tools, a trend in which railway engineering became a pace-setter, until mid-century at least, these serious deficiencies severely constrained those responsible for the design, construction and maintenance of locomotives. And in these circumstances their eschewment of sophisticated mechanisms or, indeed, of any elaboration beyond the minimum requirements of adequate operation is understandable. Thus, during these formative years, locomotive practice was governed and moulded by several interacting factors of which theoretically correct dynamic design was far from being the most important.

Faced with the necessity of improving the steadiness of locomotives by counteracting the sinuous motion, which in his

opinion was the principal cause of the trouble, Fernihough applied rim weights to the driving wheels heavy enough not only to completely balance the revolving masses but also the pistons and other reciprocating parts.

For the benefit of the Commissioners, Fernihough described his theory of the action of the balance weight which, he claimed, had not been recognised by other engineers, but which he had found to stand the test of practice.

In view of its importance as the first piece of evidence on the subject it is worth recording this practising engineer's explanation to the Commissioners in his own words.

> They [other engineers] have thought that the weight should only be applied to balance the action of the crank itself. Now I find, by laying down this action of this weight, and making a calculation of the centrifugal force at every degree of the whole circle, and at each degree resolving that force into a vertical and horizontal pressure by the ordinary rule of the resolution of forces, I find that the vertical pressure may be considered as nothing, because it merely acts upon the rail, and never lifts the wheels; the horizontal pressure is always equal and contrary at every degree of the circle to the momentum or inertia of the moving parts, which is a most singular coincidence, and very beautiful indeed: that is, if the weight is rightly proportioned, and the centrifugal force becomes more a vertical and less a horizontal pressure, I

apprehend that the momentum or inertia is exactly equal or contrary to it, so that they balance each other, and the engine becomes perfectly steady.[2]

Thus, Fernihough's theory was that the inertia force of the piston and its appendages, the main cause of the trouble, could be neutralised by inserting extra balance mass in the rim of the driving wheels such that the horizontal component of the centrifugal force generated by it equalled in magnitude the inertia force.

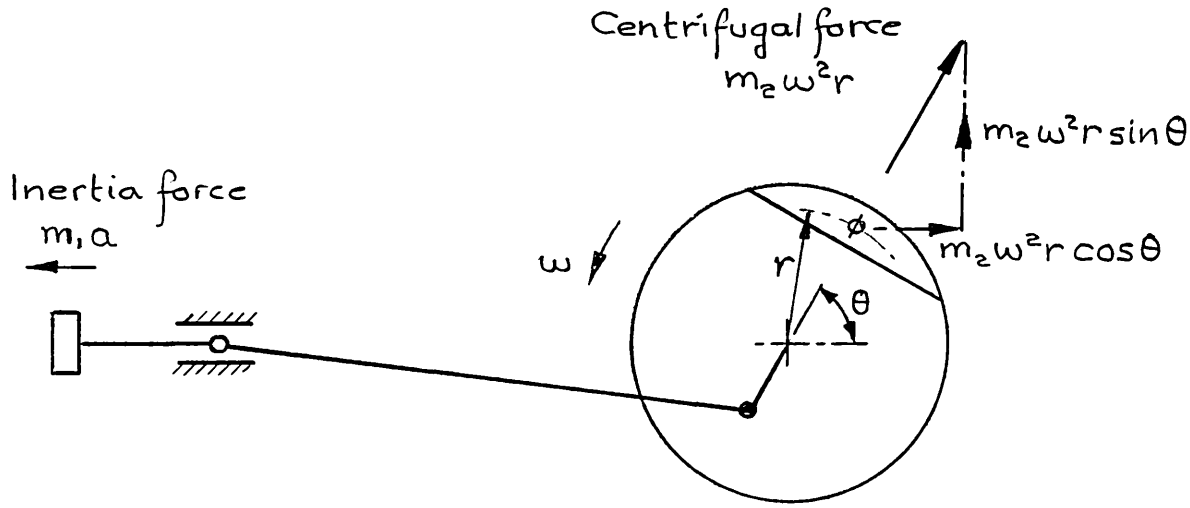


Fig.3.1 The Simple Engine Mechanism

In other words if m_1 is the mass of the reciprocating components and a is the instantaneous acceleration, then the inertia force acting along the line of stroke is $m_1 a$ and the excess balance mass m_2 is so chosen that the centrifugal force $m_2 w^2 r$, at rotational speed w, has a horizontal component $m_2 w^2 r \cos\theta$ equal and opposite to the disturbing force. By calculating the

centrifugal force due to the balance mass for a number of angular positions of the wheel and resolving it into horizontal and vertical components Fernihough verified that the horizontal effect always balanced the reciprocating parts.

However, as will be appreciated from his own words and from Fig.3.1, the procedure introduced an unwanted vertical component of the centrifugal force, which varied cyclically and possessed the same peak value as the inertia force balanced.

Pleasure in the elegance of his solution and satisfaction with the successful result of his idea are apparent from Fernihough's answer particularly so since his theory was confirmed by an improvement in the behaviour of his locomotives. Furthermore, his technical expertise clearly impressed the Commissioners for he was requested to assist them by commenting on the evidence of Daniel Gooch, the principal witness for the broad gauge party.[3]

In advocating the balance of the entire reciprocating masses Fernihough was obviously primarily concerned with eradicating the variation in the pull between engine and tender whilst discounting any possibility of adverse effects on either the locomotive or track from variation in rail pressure which, of course, was maximised by his desire for complete balance in the horizontal direction. With the relatively light six-wheeled passenger engines of his day the consequences of his 'theory' were not unduly troublesome with regard to track damage although as the work of H. Nollau was soon to show some degree of compromise was necessary in this matter. In any case, he was of the opinion that the track was suitable for the function it had

to perform and that no improvement of the permanent way was a necessary precondition for running services at increased speeds.[4]

At the request of the Commissioners, Fernihough gave his opinion. His reply gives no indication that his knowledge was founded upon quantitative data or, indeed, was other than a judgement made as a result of his own immediate experience. Nor is this remarkable. Many decisions were made on the basis of subjective views frequently of necessity. In this particular case, early crystallisation of the organisation and structure of railway companies separated the responsibility for rolling stock and permanent way between different engineers. Many years were to pass before the dynamic interaction between track and vehicle was investigated methodically. The locomotive superintendent was preoccupied with his engines; their behaviour had to be improved in the simplest manner possible. To meet economic constraints the cost of achieving this was also a significant factor. The vertical force was dismissed as nothing 'because it merely acts upon the rail'. The possibility of it actually lifting the wheel was not envisaged.

Since the utilisation of 'overbalance' became the norm in locomotive engineering, and William Fernihough's skeletal description of the principle to the Gauge Commissioners, quoted above, is the first published record of it to come to light so far, credit for the method to be almost universally employed throughout the entire history of the two-cylinder steam locomotive must be accorded to the locomotive superintendent of the Eastern Counties Railway.

2. The Emergence of a Theory of Balancing

The brief paper[5] on the subject of counterweights on the driving wheels of locomotives by H. Nollau, Chief Engineer of the Holstein Railway, brought the topic into print and thus laid the foundation of the theory of locomotive balancing.

The starting point of Nollau's analysis was the recognition that almost all locomotives exhibit a variation in drawbar-pull, 'a jolting action in connection with the tender',[6] especially when only hauling a small number of wagons or when running fast the regulator is closed and steam is completely turned off, with the consequence that the coupling gear is frequently damaged and subject to repair. In acknowledging that this inconvenience is lessened by a spring connection between the engine and tender he makes the point that such a remedy does not eliminate the cause of the uneven motion. Since such irregular motion could not be attributed to the tender or to the wagons it must be generated by the engine and he states that this opinion was confirmed by careful observation which revealed that the oscillations corresponded exactly with motion of the piston.

Before proceeding to a more detailed examination of Nollau's paper it should be emphasised that the necessity to overcome persistent, serious difficulties at different levels eventually directed the attention of some of these early engineers to the dynamic problem to be solved. Essentially these levels can be classified as 'vehicle behaviour' and 'component failure'. The evidence suggests that concern with one particular aspect of the problem led to a recognition of the

disturbing effects of the reciprocating masses and the ultimate formulation of the problem as one of securing an acceptable degree of dynamic balance.

As the previous chapter has shown, instability of the locomotive itself was of paramount importance because of the vehicle's inherent tendency to derail. Even if this potential catastrophe did not occur, the irregular motion of the engine mechanism was transmitted, via the locomotive-tender coupling to the train and hence - on passenger trains - to the discomfort and fatigue of the passengers.[7] Whereas Fernihough, for example, was preoccupied with the 'swaying' of the engine - perhaps as a result of his experience with Forrester's 'boxers' or the notoriously unsteady Braithwaite Milner locomotives on the Eastern Counties Railway - Melson and Bury saw the problem in terms of passenger comfort.

At another level, damage or failure of the coupling appears to have been the focus of other engineers. It was certainly a common experience in the working life of Thomas Hunt and on the basis of Nollau's paper, it was also the origin of his interest in the matter. Significantly the source of the trouble was identified and remedied by engineers responsible for the routine working and repair of the engines rather than by those who designed them.[8] Both Nollau and Hunt were dismissive of the idea of employing a spring coupling between engine and tender because it did not eradicate the cause of the trouble, but their approach to employing the same method, i.e. the use of wheel balance weights, to overcome the problem was vastly different. Hunt, of whom more will be said later (Section 9 of

this chapter), did not make any calculation while Nollau made a careful analysis. Having rejected as a minor factor the jolting which would occur due to a change in speed of the train, as during starting or stopping, Nollau claimed the major cause of oscillation to be the result of centrifugal force and the inertia force generated during the rotation of the driving axle.

Following consideration of the rotating parts, where necessary reducing them to equivalent weights at the crank-pin radius, Nollau gave the effective centrifugal force as

$$p = \frac{v^2}{2rg} q$$

where r = crank pin radius

q = equivalent weight of the rotating parts

v = constant velocity of the crank pin

He noted that when the crank approximately made a right-angle with the connecting rod,[10] or when the piston had its greatest speed (i.e. when the acceleration was zero), then this force alone existed.

To determine the force p' required to accelerate and decelerate the piston and its accessories he stated that the weight q' of the reciprocating parts must include the portion of the connecting-rod which rested upon the crosshead. No indication is given as to how he apportioned the weight of this component between the rotating and reciprocating masses but probably this would have been by direct weighing. That is, by placing the rod with its centres on knife edges individually

carried by separate weighing-machines. This technique, which became widely adopted in locomotive practice gave only an approximation, albeit a satisfactory one, because the motion of the rod, partly reciprocating and partly revolving and varying continuously, was complex.[11]

Following his analysis of the piston, connecting-rod and crank mechanism, which he depicted as shown in the diagram, Figure 3.2, Nollau showed that the force necessary to accelerate

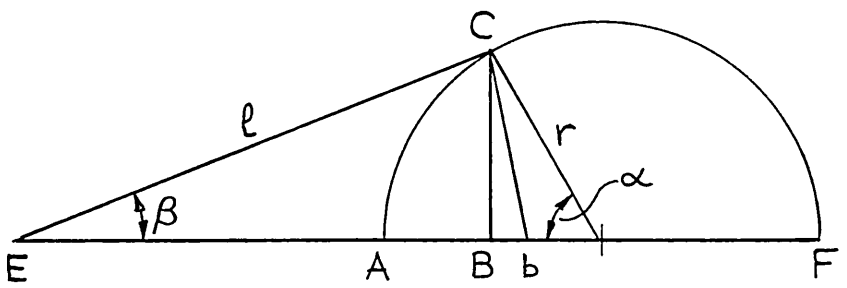


Fig.3.2 Nollau's diagram of the piston, connecting-rod and crank mechanism

and decelerate the piston and its accessories is given by the equation:[12]

$$p' = \frac{v^2 q'}{2rg}\left[\cos\alpha + r\,\frac{l^2(\cos^2\alpha - \sin^2\alpha) + r^2\sin^4\alpha}{\sqrt{(l^2 - r^2\sin^2\alpha)^3}}\right]$$

From this he noted that because of the finite length of the connecting-rod the piston inertia forces are bigger in motion to and from the top dead centre than in motion to and from bottom dead centre, and deduced that the accelerating force would vary between the limits.

1. For point A, when $\alpha = 0$, $p' = \frac{v^2 q'}{2rg} \cdot \frac{\ell + r}{\ell}$

2. For point F, when $\alpha = 180°$, $p' = -\frac{v^2 q'}{2rg} \cdot \frac{\ell - r}{\ell}$

The smaller ℓ is compared to r, the greater is the difference between these limits and for this reason alone he advocated the use of long connecting-rods as being conducive to the steady action of the engine. It is probable that this fact had already been learnt from practical experience and later, in the correspondence in The Engineer, it was noted by 'Hastings', an anonymous correspondent, who frankly admitted his inability to deal with locomotive design in a scientific manner.[13]

To reduce the analysis to manageable proportions he took the mean value of the inertia force as the one of practical importance and further, assumed a connecting-rod of infinite length, which resulted in the more tractable expression for the accelerating force

$$p' = \frac{v^2 q'}{2rg} \cos\alpha$$

which reaches a maximum value of

$$p' = \frac{v^2 q}{2rg}$$

when the piston is at dead centre.

The total disturbing force tending to push the driving axle and hence the whole locomotive alternately backwards and forwards was obtained by combining this equation with the equation for the centrifugal force due to the rotating masses, hence

$$p + p' = \frac{v^2}{2rg}(q + q')$$

or

$$P = \frac{v^2}{2rg} Q \qquad 14$$

Thus, the procedure was one of reducing the effect of the motion parts under consideration to an equivalent weight at the crank pin and then calculating the corresponding centrifugal force. Since his analysis was of a single cylinder engine to this point he extended his treatment to two cylinders, and hence to the locomotive, with their driving cranks at 90 degrees to each other and each forming an angle of 45 degrees with the horizontal axis of the cylinders, and showed that the variation in draw-bar pull of the locomotive for each turn of the driving

wheel was

$$P'' = 1{\cdot}414 \frac{v^2}{rg} Q \qquad 15$$

These disturbing forces were to be neutralised by fixing weights on to the driving wheels, opposite the cranks, such that the centrifugal force generated by the weights was equal in magnitude but opposite in direction to the disturbing forces.

3. Nollau's experimental work

Nollau's theoretical results were confirmed by testing a number of locomotives under different sets of conditions and his paper gives a detailed description of a test on an inside-cylinder, single driver engine for which he calculated the disturbing force as 5383 lb.[16] To investigate the effects of the internal disturbing forces on the behaviour of the locomotive and to eliminate the external factors (imperfections of the permanent way obviously affected the stability and riding characteristics of the engine), it was suspended by four iron rods from beams with the wheels several inches above the rails. This arrangement not only permitted freedom of movement in a horizontal plane but also, due to the elasticity of the beams, vertical movement was also possible. With the engine 'steamed' and the driving wheels rotating at their usual operating speed the whole locomotive surged backwards and forwards, synchronously with the piston movements, through a distance of about two inches although there was hardly any

lateral swinging of the smoke-box. Simultaneously the engine exhibited an 'up and down' movement which was described as 'considerable', although Nollau commented that this vertical disturbance was not usually observable since the rails prevent it but the usual wear of the tyres on the side of the crank is attributable to the phenomenon. J.E. McConnell noted the same defect in his paper given at the Institution of Mechanical Engineers during June 1848.

By adding counterweights of 51 lb, at a distance of 30 inches from the axle centre, it was not possible to observe any vertical movement even at a speed of 250 rev. min^{-1} although there was a strong surging movement, backwards and forwards, along the longitudinal axis of the machine. This was completely eliminated when the balance weight was increased to 133 lb but at the expense of the reintroduction of the vertical movement plus an appreciable sideways swing of the front part of the engine. The counter-weights were now too large to neutralise the vertical forces and since they were twice as far as the pistons from the centre-line of the engine they increased the nosing couple. From the beginning, then, it was obvious that the whole of the reciprocating weight should not be balanced. As a compromise Nollau adopted a counterbalance of 92 lb, the arithmetic mean of 51 lb and 133 lb and found this expedient successful to the extent that after about a year in service there was no evidence of wear at the coupling, in contrast to previous experience where, despite spring couplings, bolts were constantly worn and footplates torn loose. In a second test to investigate the variation in draw-bar pull the tender was

coupled to the engine in such a way that the draw gear permitted two inches of free movement between the two vehicles and when with a counterweight of 133 lb the locomotive moved off with normal speed there was no surging action between the engine and tender, but a variation in the counterbalance of about 20 lb was sufficient to re-introduce the irregular motion between the vehicles.

The paper also noted that inside cylinder engines with coupled drivers in most cases did not require balance weights because the external cranks and their coupling rods, mounted opposite the inner cranks, replaced them. And although these engines were remarkable because of their quieter operation, the author observed, this ceased to be the case as soon as the external coupling rods were removed.

Locomotives with external cylinders possessed the unpleasant characteristic that with every movement of the piston the front part of the engine was pushed from side to side. Nollau commented on the difficulty of finding the cause for this and stated that numerous explanations had been attempted, many people attributing it to the variation in load on the front springs due to the obliquity of the connecting rods but he found this argument untenable because observation revealed that there was hardly a regular movement of the springs, especially with horizontal cylinders and, furthermore, the uneven motion of the locomotive remained even when the steam was cut off. He then identified the cause as the couples brought into play.

> With inner cylinders, because of their small distance from the central axis, the force exerted by the crank at dead centre results almost only in a push along the longitudinal axis; with cylinders mounted externally, however, this force acts in a one-sided manner, and tries to turn the engine around an imaginary central axis.[18]

At this point when discussing the balancing of outside-cylinder engines he came close to recognising the effect of placing a balance weight in the rim of a driving wheel for he remarked that the weight and the piston were 'Placed at nearly equal distances from the central axis'.

Outside-cylinder locomotives with coupled driving wheels presented the most unfavourable situation from the aspect of balancing because in this case the coupling rods, instead of balancing the weight of the piston, actually added to the effect of the reciprocating parts necessitating the use of the largest counterweights although these could be suitably arranged by dividing them between all four coupled wheels.

Even three-cylinder engines were mentioned in this brief publication and Nollau pointed out that whilst in this case there was no tendency to sway from side to side, without the use of counterweights the surging along the longitudinal axis would be as marked as with any other locomotive.

4. The Mathematical Work of H. Nollau

H. Nollau was undoubtedly a competent engineer who

established the 'science' of locomotive balancing on a sure foundation. The significance of his analysis and formulation of the problem in terms of a mathematical model should not be under-estimated. It demonstrated the potential value of rational analysis as opposed to ad hoc adjustments and modifications to secure improvements but which did not enlighten the mind as to the real nature of the problem, or eliminate the actual sources of the trouble. His use of the differential calculus indicates his possession of a mathematical facility not shared by the majority of his British counterparts, and demonstrated that mathematics and mechanics could be of great utility in this particular aspect of locomotive design.

The value of the mathematical approach is that it is the only means of revealing the fundamental nature of a problem in certain situations and thus, within its limitations, permits a rational method to replace empirically determined, frequently inferior, substitutes. Clearly there are limitations since idealization, or simplification, is a prerequisite for an engineering problem to be rendered amenable to analytical treatment and this, in turn, demands the exercise of careful discrimination and sound judgement on the part of the engineer.

Attempting to evaluate the impact of mathematical methods on locomotive design is an intricate job, fraught with difficulty. Improvements could be secured without any theoretical knowledge. And in the early years of the locomotive they undoubtedly were. Engineers were not slow to recognise and adopt good practice. As shown in this chapter, simple observation revealed that engines with long, as opposed to

short, connecting rods were steadier in motion; while Thomas Hunt achieved balance in his locomotive by purely trial and error techniques. Theory, then, could explain and confirm current practice achieved through a process of evolution. But the possibility of the reverse process must not be overlooked. Writing of a later period and in particular of Lomonossoff's contributions to railway engineering M.C. Duffy makes the point that it was possible for an engineer 'who scorned complex mathematical methods' to identify and emulate the best current practice. Thus, even the results of academic research could be, unknowingly, incorporated into a contemporary design.[19]

5. H. Nollau - concluding comments

Nollau's contribution to locomotive engineering was outstanding. However, of the man himself, his education, his technical training and his career nothing appears to be known.[20]

All that can be said, based on the available evidence, that is his own paper on the subject, is that when it was published in 1848 he was the Maschinenmeister of the Holstein Railways. However, the title itself is not without ambiguity. According to Prof.Dr.-Ing. K. Mauel the word may mean 'technical leader' or 'chief engineer', although in 1848 the designation ingenieur had not yet come into use. Furthermore, he states that '...with a fair degree of certainty it may be assumed that Nollau was responsible for running the railways, hence for the locomotives and the rolling stock.'[21]

It was, then, the 'running' engineer who carefully noted the precise correspondence between the troublesome oscillations

and the piston motion and examined the problem analytically.

He also identified the salient features of the problem of balancing the various types of locomotive then in use but his analytical work, put to the test on actual locomotives, in no way provided a 'theoretical solution' to the problem. Conclusively his investigation showed that, if counterweights were to be used in the driving wheels of a locomotive, the degree of balance had to be a compromise between the diminution of the various parasitic motions, that, is, in current terminology, between nosing, hammer-blow and surging. Thus analysis provided an efficient and reliable basis upon which could be superimposed the compromise but in the determination of this latter element the expertise of the engineer was a vital constituent.

In reviewing Nollau's cogent seminal paper it is interesting to note that the only omission of practical consequence was his failure to comment upon the unbalanced couple introduced by the addition of the balance weight in the rim of a driving wheel. Because the weight and the piston assembly were not in the same longitudinal plane a couple was generated which, acting on the frame of the locomotive, tended to make it sway from side to side across the track. Possibly he recognised, but chose to ignore the effect as inconsequential. Compensating for it, or 'cross-balancing' as the procedure became designated, could perhaps have been regarded as an unnecessary refinement at the time. Not until well into the twentieth century did it become part of general locomotive practice in the United States of America.

On the basis of his evidence to the Gauge Commissioners, discussed earlier, it is not unreasonable to suppose that Fernihough had also made a mathematical analysis of the problem - and it is surely significant that he did so - but, at present there is no known evidence that he published anything on the subject or that any of his manuscript notes have survived. Accordingly, the German engineer must be credited with priority in bringing the theory of balancing into history. With his paper the topic makes the transition from prehistory to history.

Whether or not Nollau acquired the idea of 'overbalance' from Fernihough is not easily determined. Indeed on the basis of present evidence and knowledge a conclusive answer is not possible. Certainly the German did not make any acknowledgement but nevertheless the possibility of such influence cannot be summarily discounted. Fernihough gave a fairly detailed description of his ideas on the subject to the Commissioners in the autumn of 1845 and the official Report was published in 1846. Nollau's paper did not appear until October 1848. The first locomotives used in Germany were supplied, by Stephenson, from England and because of England's lead in railway technology during the 1830s and 1840s it is most likely that Continental railway engineers kept themselves informed of developments in Britain. Without question, L. Le Chatelier's book published in 1849, and discussed later, showed him to be aware of the latest developments in Germany, Great Britain and the United States of America. And it is not unreasonable to assume that other engineers grappling with the problems of the new technology had a genuine interest and a real motive for keeping abreast of the

ÉTUDES

SUR LA STABILITÉ

DES

MACHINES LOCOMOTIVES

EN MOUVEMENT

PAR L. LECHATELIER

INGÉNIEUR DES MINES

PARIS

LIBRAIRIE SCIENTIFIQUE-INDUSTRIELLE

DE L. MATHIAS (AUGUSTIN)

QUAI MALAQUAIS, 15

1849

Fig.3.3 Title page of Louis Le Chatelier's
Etudes sur la Stabilité des Machines Locomotives en Mouvement

latest practice within their own particular spheres of activity and responsibility.

6. The Work of Louis Le Chatelier

Contemporaneously with the work of Nollau, in Germany, Louis Le Chatelier, in France, was engaged in similar experimental work on locomotives and also in the preparation of his comprehensive treatise Etudes sur la Stabilité des Machines Locomotives en Mouvement,[22] Fig.3.3, which was published in 1849.

Representative of his experimental work was his test on an outside-cylinder long-boiler passenger locomotive, suspended by ropes in the workshops of the Orleans Railway. The horizontal movements of the locomotive were traced out by a pencil fixed to the buffer beam, the paper being arranged to move with the vertical movements of the pencil and thus maintain contact and produce a continuous curve. These tests were carried out at rotational speeds of the driving wheel of up to three revolutions per second, corresponding to a track speed of 57 kilometres per hour, under conditions of no balance, partial balance and complete balance. These yielded the following oscillation diagrams:[23]

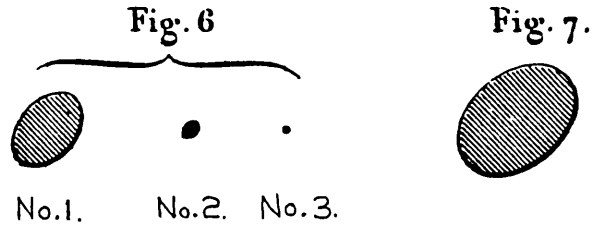


Fig.3.4 Le Chatelier's oscillation diagrams from a passenger engine

No.1 Without any counterweight

No.2 With a partial balance of 151 kg referred to the crank-pin

No.3 With the total balance of 247 kg.

The tests revealed that for a given state of balance the magnitude of the free oscillation was independent of the speed since the diagrams obtained were the same for all tested speeds. Furthermore they gave a direct measure of the nature and extent of the parasitic motions due to the disturbing forces and also of the effectiveness of the balance weights in reducing and eliminating them.

Excluding shocks due to track imperfections this engine, in the balanced condition ran steadily on the track at a speed of 80 to 90 km hr^{-1} although, when the balance weights were removed, the oscillatory motion with the accompanying violent concussion of the draw-gear returned.

Results of these investigations, carried out with the cooperation of MM Polonceau and Petit of the Orléans Railway and the Northern Railway of France, respectively, were published in the Etudes. In this book of five chapters plus eight appendices (Pièces justificatives) the author treated the subject methodically and thoroughly, defining the various disturbing forces, mathematically analysing the mechanics of the machine and illustrating his theories with numerical examples. This treatment of the subject together with the extensive coverage, 144 pages, undoubtedly laid the foundation for a more methodical approach to the matter in the design and construction of locomotives.[25]

Le Chatelier gave a consideration of both passenger and goods locomotives with outside and inside cylinders, with single and coupled driving wheels. He also reviewed, with regard to their stability, Crampton locomotives, American machines, and engines with inclined cylinders. Indeed his book indicates quite clearly that he was aware of contemporary work in this field in both England and Germany, and includes details of Nollau's paper, McConnell's paper to the I.Mech.E., and Heaton's patent of 1848.

Like Nollau, Le Chatelier derived an equation for the inertia force, which he expressed as:

$$\pi = \frac{q' v^2}{g r}\left[\cos\alpha + r\,\frac{l^2(\cos^2\alpha - \sin^2\alpha) + r^2\sin^4\alpha}{\sqrt{(l^2 - r^2\sin^2\alpha)^3}}\right] \qquad 26$$

and achieved a simplification by supposing the connecting-rod to be always horizontal, that is, of infinite length, in which case the equation reduced to

$$\pi = \frac{q' v^2}{g r}\cos\alpha \qquad 27$$

which possesed a maximum value of $q'v^2/gr$ when α had the two values 0° and 180°.

Thus, Le Chatelier, like Nollau, derived the mathematically exact equation for the piston acceleration but not considering it amenable for use in design calculations reduced it to a single term by adopting the simplifying assumption of a connecting-rod of 'infinite length'. Mathematical exactitude was partially sacrificed to mathematical tractability or practical utility. There was nothing unreasonable in this course of action since the number of variables influencing the stability of a locomotive in motion was so great, and some of them were, at any one time, indeterminate that it would have been meaningless to have attempted a mathematically rigorous and precise evaluation of the disturbing force generated by the inertia of the reciprocating masses. Le Chatelier obviously considered the reciprocating masses to be the most significant of these and furthermore he determined the error introduced by his simplification which he judged acceptable within the customary design parameter of connecting-rod to crank ratios.

As Nollau's paper had indicated, acceptable performance - i.e. freedom from snatching in the draw gear - was achieved within the limits of about plus or minus 20 lb in the requisite balance weight of 133 lb to eliminate this tendency.[28] Thus deviation of up to 15 per cent from his calculated value gave an operationally 'correct' design value for the magnitude of this component. Whilst the German engineer did not quantify the error introduced by his simplification, Le Chatelier briefly commented upon the matter. Noting that for the usual design proportions of the connecting-rod being five times the length of

the crank the maximum error was only about 12 per cent and approximately half this amount for goods engines.[29]

Later analysis also achieved the same simplification, either by using a binomial expansion to give an approximation for piston displacement, and hence via a double differentiation, the acceleration or by neglecting the terms $\sin^4\alpha$ and $\sin^2\alpha$ in the Nollau-Le Chatelier expressions for acceleration. Hence,

$$\frac{v^2}{r}\left[\cos\alpha + r\,\frac{l^2(\cos^2\alpha - \sin^2\alpha) + r^2\sin^4\alpha}{\sqrt{(l^2 - r^2\sin^2\alpha)^3}}\right]$$

is more simply expressed as

$$\frac{v^2}{r}\left[\cos\alpha + \frac{r}{l}\cos 2\alpha\right]$$

an approximation which produces a degree of accuracy sufficient for the values of the ratio of crank to connecting-rod length commonly used in practice.

During the present century, when considering the balance of the reciprocating parts of high-speed engines and greater accuracy was required, the approximate method was employed, and extended to yield the required degree of accuracy, by expressing the piston acceleration in the form of a Fourier series. For example,

$$\text{acceleration} = \frac{v^2}{r}\left[\cos\alpha + A_1\cos 2\alpha + B_1\cos 4\alpha + C_1\cos 6\alpha + \ldots\right]$$

where A_1, B_1, C_1, etc. are coefficients. For a connecting-rod five times the length of the crank, the ratio used by Le Chatelier, these coefficients have the values,[30]

$$A_1 = 0.2020$$

$$B_1 = 0.0021$$

$$C_1 = 0.000022$$

As this equation shows the magnitude of the components of acceleration diminishes rapidly whilst their frequency increases, again illustrating the acceptability of the simplification of these two engineers but also indicating another practical difficulty in attempting to achieve a theoretically correct balance. The components of acceleration, and hence of force, to be balanced are multiples of the driving-wheel speed and would thus require balance weights to rotate at twice, four times, six times, etc. the speed of the locomotive driving wheels. Such a complexity was never seriously contemplated throughout the entire history of the steam locomotive and, indeed, even in balancing of motor car engines, although it was tried, the practice never became established. Nevertheless, apart from the locomotive, the general trend to higher speeds and powers has accentuated the importance of the frequency at which forces are applied as a significant contributory factor to the generation of noise and vibration, and hence of their control. To evaluate how far the actual design calculations departed from what was theoretically, or mathematically possible it is convenient to consider further the

simplification of Le Chatelier's expression for acceleration given above, i.e. acc. = v^2/r [cosα + r/ℓ cos 2α]. From this it follows that the corresponding inertia force of a piston for an engine mechanism with a connecting-rod of finite length, may be represented by the equation,

$$F = m\frac{v^2}{r}\left[\cos\alpha + \frac{r}{\ell}\cos 2\alpha\right]$$

Because this equation is difficult to deal with as a whole its two terms are generally considered separately in the following manner. The first term,

$$m\frac{v^2}{r}\cos\alpha$$

is the force that would be generated by the actual mass, m, concentrated at the crankpin and revolving at crank speed. (As has been seen earlier, this is obtained by reducing the effect of the reciprocating components to an equivalent mass at the crank pin.) In fact, this defines the motion of the piston as simple harmonic, or that which would be obtained with a connecting-rod of infinite length. For convenience, this is known as the primary force. The second term,

$$m\frac{v^2}{r}\cdot\frac{r}{\ell}\cos 2\alpha$$

is considered to be the force set up by an imaginary mass, m, concentrated at the crankpin and rotating twice as fast as the actual crankpin. This effect is called the secondary force, and as has been noted, has been neglected in locomotive design from the beginning. Because the ratio of the length of the connecting-rod to the length of the crank is usually large, the secondary forces are small, and in the case when the cranks are at right-angles - the norm in two-cylinder engines - the secondary force for one set of reciprocating masses is always balanced by the secondary force for the reciprocating parts on the other side of the locomotive, although these forces do not act through the centre of gravity of the vehicle and thus give rise to a secondary couple.

From the earliest conscious attempts to balance the conventional two-cylinder locomotive, then, considered theoretically only a partial balance has been sought in practice. Engineers have contended with the primary disturbing forces which not only cause the troublesome variation in draw-bar pull but because of the lateral separation of cylinder centre-lines, greater in outside-cylinder locomotives than in inside-cylinder engines, introduced a nosing couple which, because it occurred in the plane of the cylinders, was resisted by the side pressure between the wheel-flanges and the inside of the rails.

7. D.K. Clark

The subject was introduced to the English-speaking world by the publication, in 1852, of D.K. Clark's writing on the subjects of 'Conditions of Stability', 'Internal Disturbing Forces', 'Balancing the Locomotive', sections of his Railway Machinery which were published in parts from June 1851 onwards. In a brief historical summary, having acknowledged the earlier work done by McConnell, on the Birmingham and Gloucester Railway, Messrs Braithwaite and Milner on the Eastern Counties Railway, and Messrs Sharp and Roberts, of Manchester, all of whom had employed counter-weights between the spokes of driving wheels to balance the revolving masses, he then paid tribute to W. Fernihough for the idea of increasing the magnitude of this counterweight to balance the reciprocating masses. According to Clark, English engineers were somewhat tardy in recognising the importance of reciprocating balance and preferred to increase stability by the artifices, mentioned in Chapter 2, of lowering the centre of gravity, extending the wheelbase and providing a stiff coupling between the engine and tender. He obviously shared Fernihough's dismissal of variation in pressure between wheel and rail as of little or no consequence and accepted his solution as the attainment of 'a complete balance'. Clark's view was, in his own words,

> The truth is, that centrifugal disturbances vertically, however potently it may affect the motion of carriages and other lighter vehicles, is by far the least important element of instability in locomotives.[32]

However, the substance of Clark's words on the subject was Le Chatelier's treatise to which his indebtedness was acknowledged. Starting with a consideration of the nature of the internal disturbing forces generated by the inertia of the mechanism he defined the parasitic motions brought into play as sinuous, pitching, rolling, and longitudinal reciprocating and then went on to a detailed examination of these with the assistance of some numerical examples taken from Le Chatelier's work and converted into English units. However, Clark's presentation was a complete contrast to that of Nollau's brief paper and the book of Le Chatelier, in that it is devoid of mathematical analysis. There is not the slightest hint that the calculus or trigonometry could contribute anything meaningful or useful to understanding or to successful engineering practice, and even the use of algebraic expression was restricted to a minimum and most elementary form. Thus, whilst the Continental engineers concisely and generally expressed centrifugal force as

$$\frac{qv^2}{rg}$$

where the symbols possessed defined meanings, Clark instructed his readers on how to determine this by the application of a rule:

> Multiply the weight in pounds by the square of the velocity in the circular path, in feet per second, -

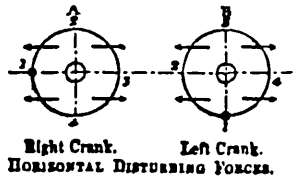
divide by the radius of the circle in feet, - and by 32. The quotient is the central force in pounds.[33]

Obviously, his work was directed to a different category of readers and reflects the fact that educationally, the engineers of France and Germany were in advance of their British counterparts with respect to the application of mathematics and scientific theory to practical engineering problems. However, accepting this situation as the predicament facing Clark, when in his leisure time, following the feverish activity of the years of the railway mania, he sought to produce his book on locomotive engineering his work must be judged on his ability to give an insight into the working of machinery for engineers whose only technical education was, almost universally, that gained in the school of practical working experience. In these circumstances a diagram such as Fig.3.5[34] showing the horizontal disturbance of a locomotive in motion, due to the inertia of the mechanism would convey more than an equation of the form

$$\frac{1}{2}\frac{Qv^2}{gr}\, e(\cos\alpha - \sin\alpha)$$ [35]

TABLE, No. LXXXVI.—SHOWING THE HORIZONTAL DISTURBANCE OF A LOCOMOTIVE IN MOTION, DUE TO THE INERTIA OF THE MECHANISM.

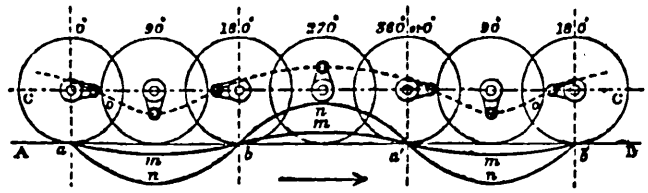
	Direction of the Disturbing Force, that of the Progressive Motion of the Engine being thus ———→ During the successive parts of a Revolution.			
	1st Quarter.	2d Quarter.	3d Quarter.	4th Quarter.
Crank A	←	→	→	←
Crank B	←	←	→	→
A and B combined	⇐	↜	⇒	↝
Nature of the compound disturbance produced.	Direct Backward Impulse to the whole Machine.	Horizontal Oscillation, swaying head of engine to the left.	Direct Forward Impulse to the whole Machine.	Horizontal Oscillation, swaying head of engine to the right.



(a) (b)

Fig.3.5 D.K. Clark's diagram showing the horizontal disturbance of a locomotive in motion

Similarly the lines m and n in Clark's diagram, Fig.3.6,[36] drawn to scale vertically, give a clear indication, in graphical form, of the variation in vertical force between wheel and rail for a mass, of 2 cwt., revolving at the crankpin at speeds of 25 and 50 miles per hour respectively, and how this variation coincides with the motion of the crankpin.



MOTION OF LOCOMOTIVES.—Illustration of the Vertical Action of Centrifugal Force on the Driving Wheel, at 25 and 50 miles per hour.

Fig.3.6 D.K. Clark's diagram illustrating the variation in vertical force between wheel and rail

Whereas, in a book of 144 pages, Le Chatelier used only ten figures to illustrate his text Clark in his five short chapters employed over thirty diagrams, including two from the Frenchman's book. From the work of both Nollau and Le Chatelier and his own investigations on the Caledonian Railway, Clark drew some conclusions. Even running of inside-cylinder locomotives was achieved by sizing the balance weight to counteract the sinuous motion although this was significantly less than that required to balance the longitudinal oscillations. The limitations of the value of calculated weights were implied by his reference to Nollau's experiment in which a counter-weight of only 65 per cent of the whole distrubing weight gave very good results although it was less than would have been derived by calculation to balance the sinuous action. Similarly, Gouin's inside-cylinder, 2 - 4 - 0, engine built for the Orlean's Railway worked steadily with but 60 per cent of the whole disturbing weight balanced whereas 78 per cent would have been necessary to counteract the sinuous motion. And he

summarised his findings,

> In general, for inside cylinders, a counterweight in the wheels equivalent to three-fourths of the gross disturbing weight on each side of the engine, is practically sufficient to secure the external stability of the engine on the rails. For outside cylinders it ought to be equivalent to the whole, or, in single engines, not less than seven-eighths of the weight.[37]

From his considerations Clark then gave four practical rules for the application of counterweights, covering the following types of locomotive:

(a) Outside - Cylinder Single Engines
(b) Outside - Cylinder Coupled Engines
(c) Inside - Cylinder Single Engines
(d) Inside - Cylinder Coupled Engines

The British locomotive engineer, from the mid-1850s, relying on Railway Machinery, the most authoritative English-language text available, was guided in the matter of balancing by the following rules, Fig.3.7, augmented by a few practical instructions, such as distributing the balance weight over at least two or three spaces between the spokes of the wheels, to distribute and reduce the unequal wear of the tyres by 'vertical action', and the tendency to slip at high speeds, and making the reciprocating parts as light as possible.[38]

RULE I.—*To find the Counterweight for Outside-Cylinder Single Engines.* Find the total weight, in pounds, of the revolving and reciprocating masses for one side, namely, the piston and appendages, connecting rod, crank, and crank-pin, (the crank being referred to the pin)—multiply by the length of crank in inches,—and divide by the radial distance, in inches, of the centre of gravity of the space to be occupied by the counterweight. The result is the counterweight in pounds, to be placed exactly opposite to the crank.

RULE II.—*To find the Counterweights for Outside-Cylinder Coupled Engines.* Find the separate revolving weights, in pounds, of crank-pin, coupling rods and connecting rod, for each wheel,—also the reciprocating weight of the piston and appendages, and half the connecting rod; divide the reciprocating weight equally between the coupled wheels, and add the aliquot part, so allotted, to the revolving weight on each wheel. The sums so obtained are the weights to be balanced at the several wheels, for which the necessary counterweight may be found by Rule I.

RULE III.—*To find the Counterweight for Inside-Cylinder Single Engines.* 1st, To find its value. Find the total weight, in pounds, to be balanced on each side, as in Rule I.;—multiply it by the sum of the widths apart centres of the cylinders and the wheels, in inches,—and divide by twice the width apart of the cylinders;—subtract the quotient (A) from the total weight, leaving a remainder (B),—square the quantities A and B, add the squares, and find the square root of the sum. This root is the resulting weight in pounds, to be balanced at the crank-pin, for which the counterweight may be found by Rule I.

2d. To find its direction. Divide the greater weight (A) by the less (B). The quotient is the denominator of the fraction of which the numerator is 1, which expresses the inclination of the direction sought, with the centre line of the near crank, diverging *from* the off crank.

RULE IV.—*To find the Counterweights for Inside-Cylinder Coupled Engines.* Find the value and direction of the counterweights for the inside revolving and reciprocating masses to be balanced, as in Rule III.; and key the driving wheels on the axle in such positions as to place the outside cranks in the direction so found, or key on the cranks themselves as required, if independent of the wheels;—find the total weight of the outside cranks and coupling rods, referred to the inside crank-pin,—and, if less than the inside weight, subtract the outside weight from it, and distribute the difference between the coupled wheels, to be balanced according to Rule I.;—or, if greater, balance the difference by counterweights *opposed* to the outside cranks.

Fig.3.7 D.K. Clark's rules for the determination of balance weights

Thus the theory of balancing initiated by Nollau and developed by Le Chatelier was transmuted by D.K. Clark into a set of working rules and the French engineer's influence on British locomotive design, if it occurred or to the extent it did so, was via Railway Machinery and in unrecognisable form because by the time it was presented here it was diluted and stripped of its mathematical and scientific form. Creditably, Clark perceived the deficiency and weakness in British practice and acted to remedy the situation. Recognising the immediate practical value of the work of Nollau and Le Chatelier, without delay he translated their results into a set of instructions suitable for use by British engineers.

8. Rules-of-thumb

Arguably such rules, if they were employed correctly, had some immediate value by enabling the ordinary locomotive designer to benefit from the theoretical work and the experience of leading engineers and to produce machines with acceptable running characteristics. However, the danger with established codes of practice and design rules is that, by their very nature, they tend to relate to outdated or conventional designs and thereby have little or nothing to contribute to future development. In extreme circumstances they can prove positively harmful to later generations of practitioners who apply them in a routine manner with no understanding of the real nature of the problem. And this proved to be the case with the Le Chatelier-Clark proportions for balance weights. They were related to the small relatively light-weight (20 to 30 tons),

short-wheelbase six-wheeled locomotives of the mid-century and were entirely inappropriate at the end of the century and even more so in the third decade of the present century. Thus the rules which gave good balancing when they were formulated were responsible for so much bad practice fifty years and more later; the use of the adjective 'good' here implies no more than an acceptable degree of stability as judged by contemporary engineers. In their view and with their experience of very unsteady unbalanced engines the improvements achieved must have seemed highly satisfactory but it must be recognised that their apparent success was based upon a total neglect of what later became known as the 'hammer-blow' effect.[39]

Small incremental improvements in performance accompanied by the persistent demands for simplicity and cheapness in construction and maintenance with, above all, the paramount requirement of no diminution of reliability inhibited innovation in design and reinforced the custom in which many of the variables involved in design were summarily dealt with by long-established rules-of-thumb, without the contribution of much thought. In these circumstances the existence, or even the availability, of a theoretical basis for design decisions was not of relevance or, generally of much interest.

The 'theory' of balancing as it was defined in the middle of the nineteenth century is open to the severe criticism that it was founded on the magnitude of the disturbing forces only rather than, what would have been a more difficult task, on the relationship between the magnitude of these forces and the mass and inertia of the vehicle. In other words, on the effect

of these forces on the engine. Nevertheless, as the generally accepted and used method of influential engineers it could have been anticipated that it would have had a tolerably successful and widespread adoption by practising locomotive designers during the second half of the nineteenth century and whilst the surviving pictorial evidence[40] suggests that the technique of balancing, as a deliberate act to promote even motion of the engine by the use of counterweights, became the norm, there is also evidence[41] to suggest that the actual balancing was defective.

Caution is necessary, however, in drawing conclusions from contemporary illustrations. Collectively they provide evidence of the unmistakable trend towards the increasing use of balanceweights in the wheels of locomotives and the individual drawing, if it shows them, is likely to be accurate because of this. More problematic is the drawing which does not indicate their use. M. Duffy has conjectured that possibly such machines were balanced by the owning company upon receipt from the manufacturer and, of course, this is not unlikely.[42] But another interpretation is possible, that is, the locomotive was balanced by the manufacturer but the draughtsman or artist chose not to incorporate the feature in his depiction of the machine. Improbable though this argument may seem, there is some evidence to support it.

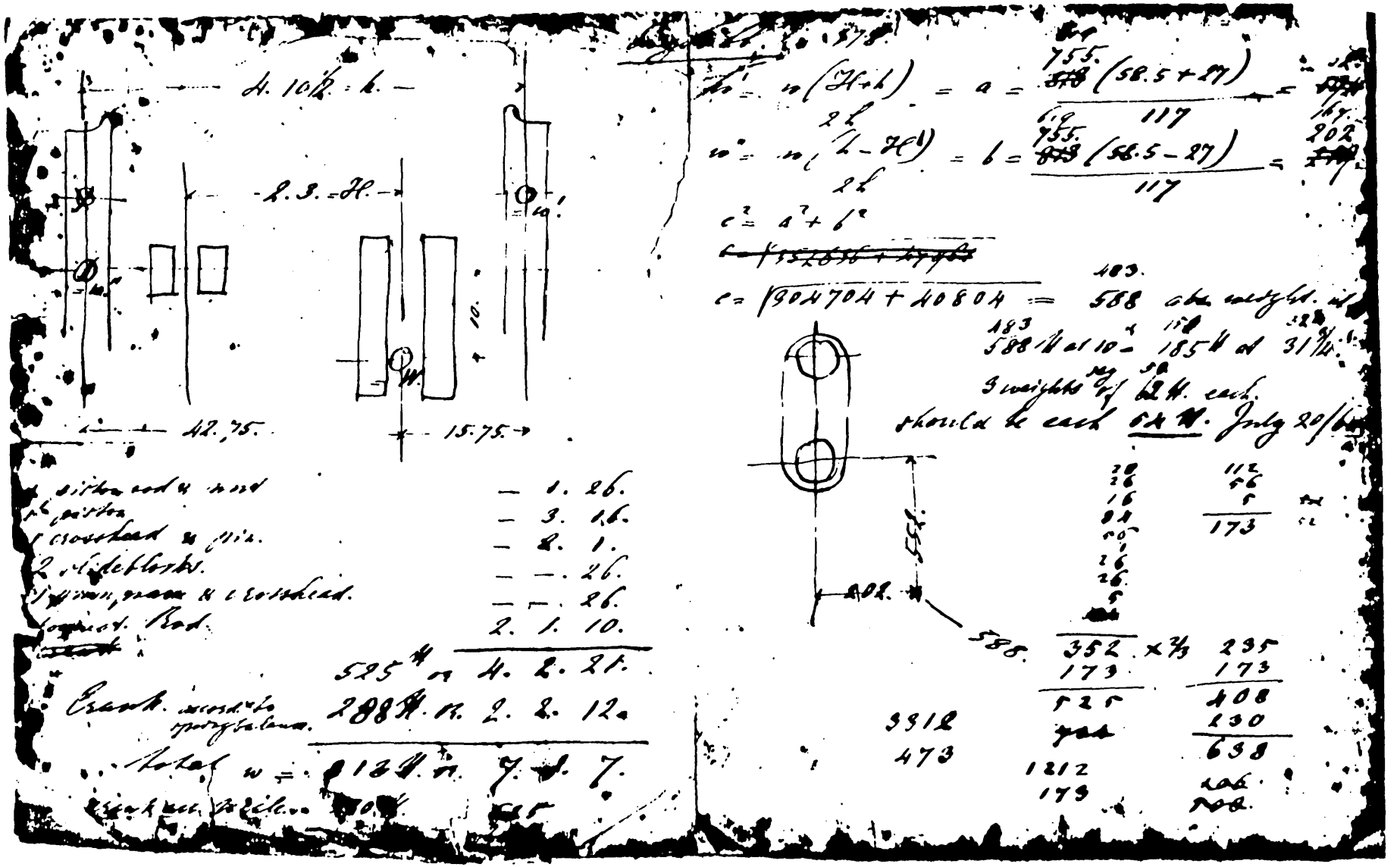


Fig.3.8 Balancing calculations for Beyer, Peacock 2-2-2 locomotive for the Edinburgh & Glasgow Railway, 1856

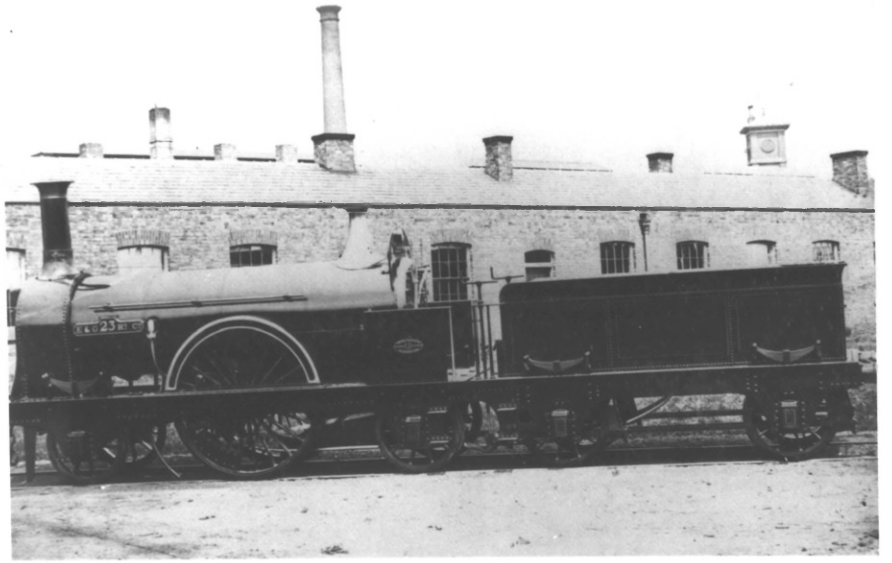


Fig.3.9 Edinburgh & Glasgow Railway, 2-2-2 locomotive, 1856

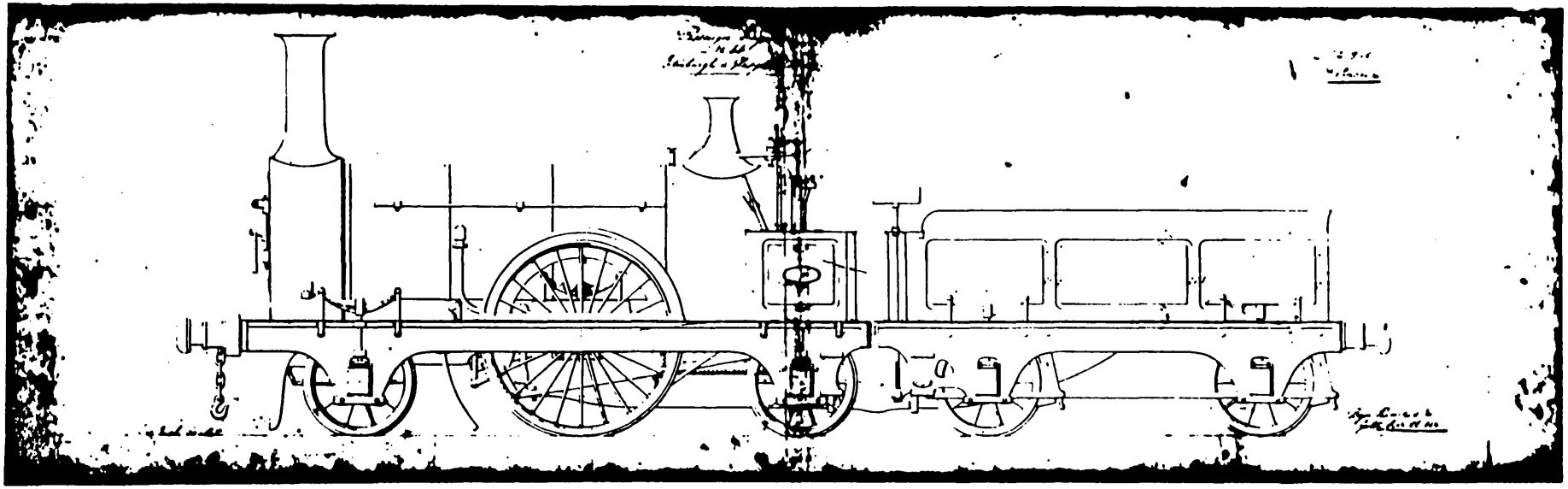


Fig.3.10 Beyer, Peacock 'As built' drawing of the Edinburgh & Glasgow Railway 2-2-2 locomotive, 1856

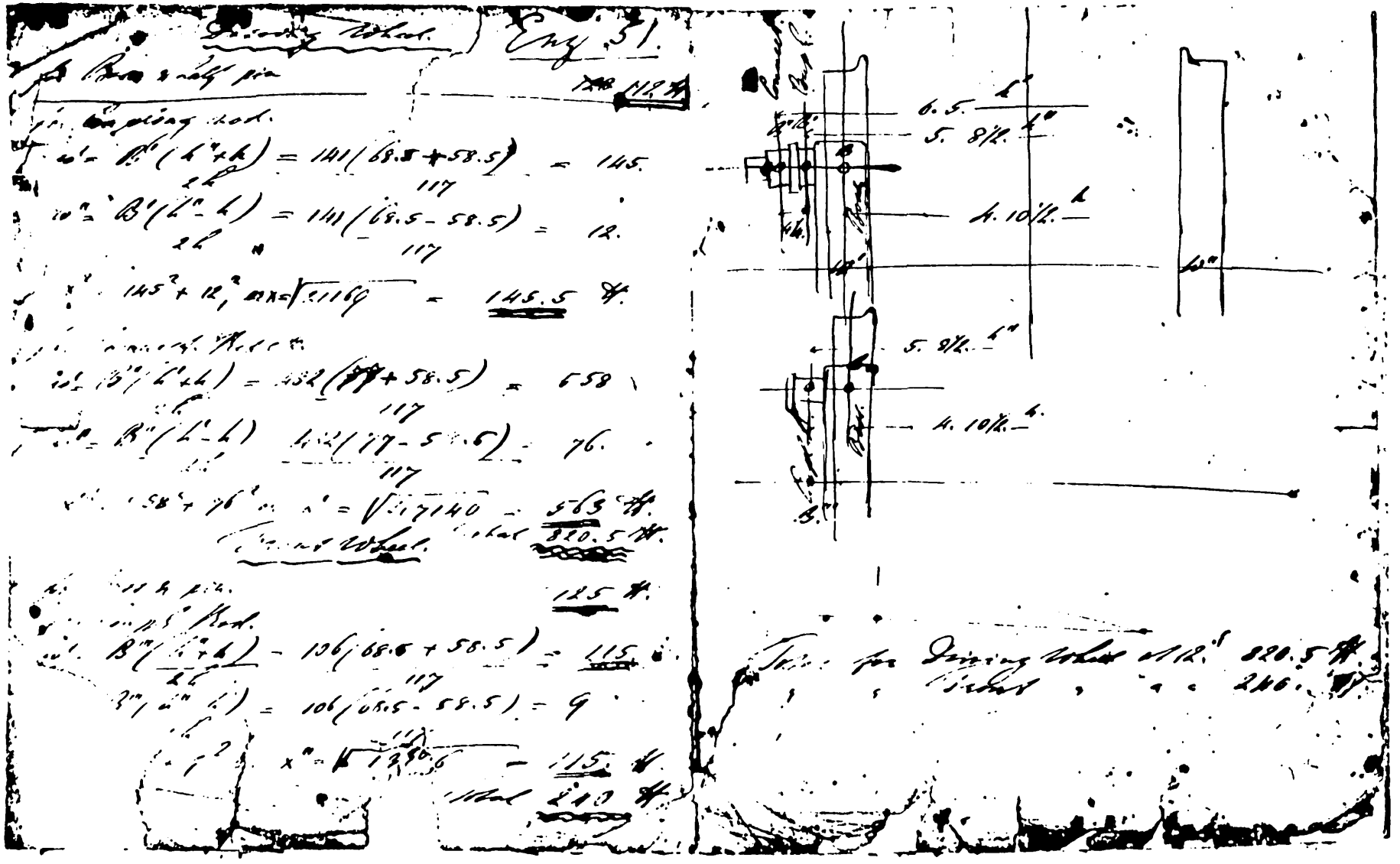


Fig.3.11 Balancing calculations for Beyer, Peacock 0-4-0T engine for the Great North of Scotland Railway, 1855

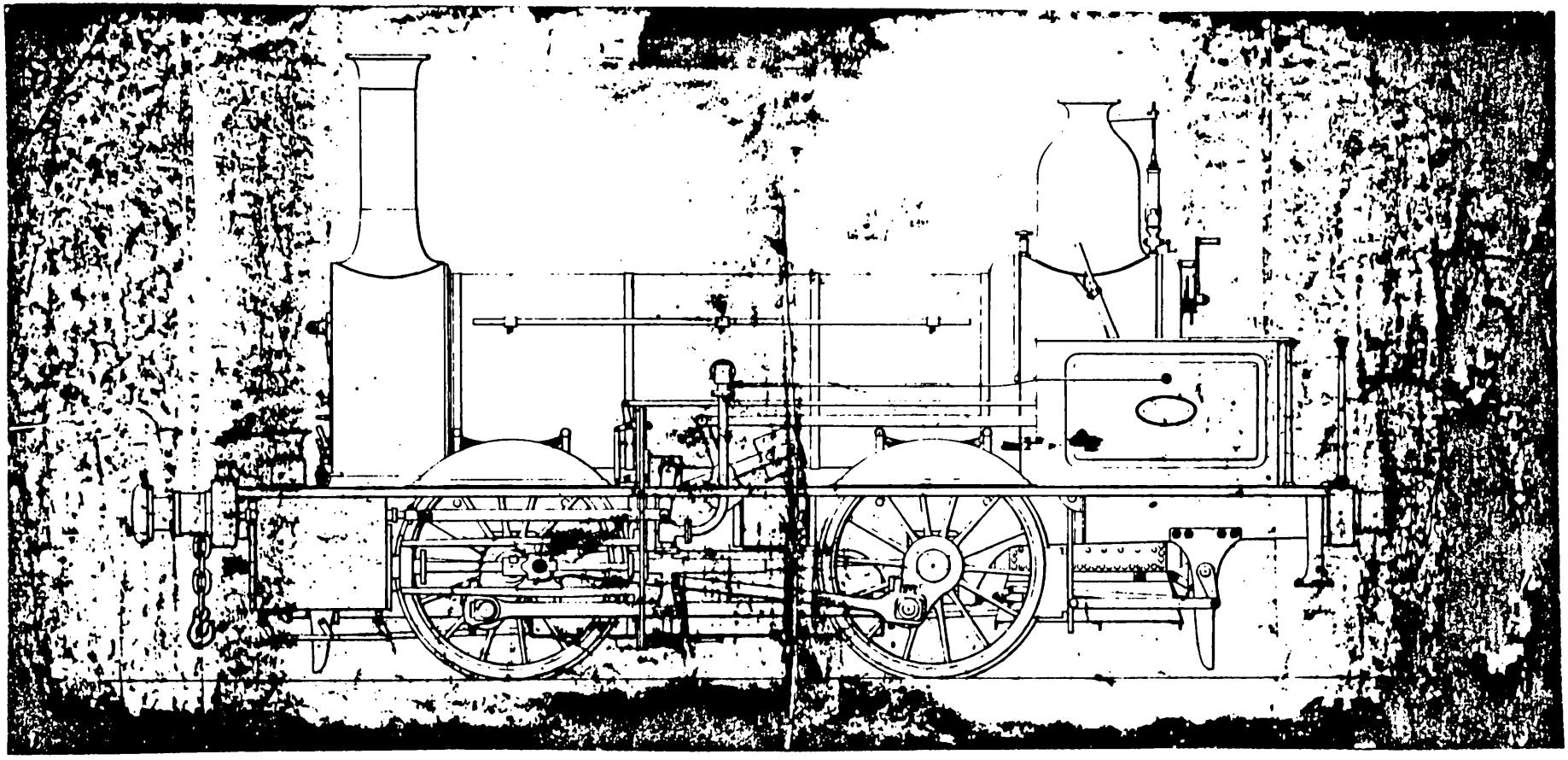


Fig.3.12 Beyer, Peacock 'As built' drawing of the Great North of Scotland Railway, 0-4-0T engine, 1855

In 1856 Messrs Beyer, Peacock built six 2-2-2 locomotives for the Edinburgh & Glasgow Railway Company and the actual balancing calculations for this design still survive, as do the 'as-built' drawing plus a photograph of the engine and its tender. From the year 1856 this firm had every class of locomotive they built photographed and the surviving illustrations provide excellent pictorial evidence for the historian. Thus in this particular case there is the balancing calculation (Fig.3.8), the photograph (Fig.3.9) showing the balance weight on the driving wheel but an 'as built' drawing (Fig.3.10) showing an unbalanced locomotive!

Similarly the calculation (Fig.3.11) exists for an 0-4-0T engine built for the Great North of Scotland Railway in 1855 - the earliest documentary calculation discovered in this research - but the 'as-built' drawing (Fig.3.12) does not show a balanced engine.[43]

Quite possibly aesthetic reasons were responsible for the omission of this asymmetrical, but technically necessary, protuberance. Many later photographs 'posed' locomotives with cranks downwards, coupling-rods horizontal, and balanceweights conveniently hidden by splashers.

9. Confused Views

A decade after the publicity given to the stability of the locomotive engine on the track by the Gauge Commission and five years after the publication of the works of both H. Nollau and L. Le Chatelier an interesting, and at times acrimonious, correspondence in the columns of The Engineer revealed an

extraordinarily wide divergence of opinions on the effect of the extra balance weight on the rails.[44] Additionally, it provides us with some indication of the slow dissemination, or acceptance and utilisation, of locomotive design theory.

Indeed, so eccentric and erroneous were some of the ideas put forward with writers manifestly lacking worthwhile knowledge on the topic that an exasperated plea from the anonymous author, 'C', of the articles which started the correspondence suggested that the contributors should determine the facts of the case by trial

> ...before wasting their time in speculative nonsense, and pronouncing dogmatically upon subjects which obviously they do not comprehend.[45]

And yet in the second of his articles 'Internal Disturbing Causes - Horizontal Oscillation, its Prevention by Counterweights' in considering the question whether the vertical play of the extra balance weight does any harm, the author replies negatively and emphatically.

> The vertical action expends itself harmlessly upon the non-yielding rails, downwards; and upon the heavily-loaded driving springs upwards. No sensible instability results from it.[46]

This is obviously the contemporary view of a locomotive engineer who, seemingly, genuinely failed to appreciate the potential hazard of an 'overbalanced' engine for the satisfactory service of the permanent way. However, this view was immediately challenged by another correspondent who asserted that it was

> Not correct to remedy one evil by means which will evidently produce another and, as many believe, a greater one.[47]

Notwithstanding all that had gone before, as late as 1856 the cause of the oscillation of the locomotive was specifically attributed to influences external to the machine itself. The source was identified as the permanent way; deficiencies in the track, curves and conical tyres, sleepers and ballast. Indeed the author of this view, although not disputing the need to balance the revolving masses, was untroubled by any doubts on this matter to the extent of categorically denying any influence of the reciprocating parts on the stability of the vehicle,

> ...but let us once obtain a really <u>permanent</u> way...On such a road the unbalanced engine of 1856 will hold the 'even tenor of its way', and smile undisturbed by the puny efforts of reciprocating parts to cause a wrinkle on the brow of the go-a-head <u>whole</u>.[48]

In a further communication[49] on the topic, including some elementary calculations purporting to illustrate his argument, and claiming to have investigated the subject theoretically in combination with some simple experiments, although their nature was not revealed, the correspondent claimed to have established that the disturbances under discussion arose from causes external to the engine itself. Such views suggest a lack of practical experience as well as betraying an ignorance (perhaps not surprising) of elementary mechanics. However, if they were genuinely held and the writer occupied a position of responsibility in the design or operating departments of a railway company the existence of some badly balanced engines was inevitable. And there were many such locomotives in the middle of the nineteenth century.

The importance of the subject can be appreciated from the lively correspondence it engendered and sustained over a period of several months and as already mentioned its value to the historian is evidence of the disparate and often contradictory views held by the various writers. Nevertheless many of them were held with conviction and tenacity emphasised by large measures of denigration and vituperation as deemed appropriate by the writer. Perhaps, not surprisingly, almost the entire correspondence was above either just initials or pseudonyms. At the time this, the unhelpful and undesirable incursion of animosity, arrogance, and condescension was noted and regretted.

The value of this evidence is somewhat diminished because it has not so far been possible to identify either the

engineers who held these views or the positions they held. Because of the significance of the topic and the interest in it displayed at the time an examination of the correspondence reveals what appears to be two remarkable omissions. No contributor actually illustrated his method of determining the magnitude and position of balance weights and none of the prominent locomotive superintendents of the period, from their position of influence and authority, availed themselves of the opportunity to give enlightenment where it was so manifestly needed.

A possible and plausible explanation for this could be that whilst the opinions expressed were largely theoretical and contributed by those with an interest in this aspect of locomotive design, the actual balancing of the engines was the responsibility of engineers who worked on the basis of empirical rules and subsequently achieved an optimum performance by making adjustments to the vehicles once they were in service. Such a procedure was probably well established by the mid-nineteenth century and is testified by Thomas Hunt who, writing of events forty years earlier when he was the locomotive superintendent of the North Union Railway, described his experience with the engines under his command which were all of the 'Bury' type. Fractured draw-pins between locomotive and tender were almost a daily occurrence and to resolve this problem although a draw-spring was considered the idea was abandoned in favour of rim balance weights in the driving wheels opposite each crank. His approach to the task is described in his own words:

> I made no preliminary calculation as to the quantity of live weight to be balanced, but applied such a weight as I thought might be under rather than above that required, and if in the working of the engine my expectations were realised, I purposed increasing the weight in other engines until I arrived at something like a successful result.[50]

In the first instance this method obviously depended upon an estimate on the part of Hunt followed by trial-and-error adjustments until an acceptable standard of behaviour was secured. Thereafter, the engineer was in possession of some experience and could make a more knowledgeable and accurate assessment of the initial balancing mass to be employed and thus the number of subsequent adjustments could be reduced. From his own words, 'something like a successful result' it is apparent that a technically perfect result was neither expected nor sought and indicates the commonsense attitude of the practising engineer to 'compromise' as the norm in the solution of technological problems. Since there were many other factors and influences contributing to the unsteadiness and motion of a locomotive in its daily work it was obviously a pointless exercise, from both economic and technical considerations, to seek the ultimate in balancing the machine.

Whatever improvement Hunt secured was not regarded as the ultimate because he subsequently employed a draw-spring coupling between engine and tender in addition to balance weights.

In these circumstances it is not difficult for us to appreciate that calculation seemed to offer no advantage to the contemporary engineers. The locomotive was a crudely-built machine, made by men who had hardly any craft skills and subsequent adjustments and modifications were necessary on the majority of engines built.[51] Thus it would not be unexpected or unusual for balancing arrangements to require subsequent alteration.

10. The Deteriorating Situation

However, in certain quarters the current state of the art was deemed to be unsatisfactory and the need for a more scientific approach to the whole business of locomotive design and construction in general and the balancing of engines in particular was appreciated and disquiet was voiced. The advantageous position of the French had been noted by a contributor to the correspondence in The Engineer during 1856[52] and a decade later the methods of English engineers were questioned in the pages of Engineering. T.W. Rumble, an engineer with chambers in Westminster, lauded the scientific approach of Le Chatelier and

> because of the paramount importance of the subject to all connected with the manufacture or repairing of locomotives, I am at present preparing a translation of the work, which will be shortly published if arrangements can be made with the author.[53]

Whether or not arrangements of any sort were made the work never appeared in print in English. Nor is it likely that it would have served a very useful purpose if it had. Almost certainly it would have been beyond the comprehension of many, maybe the majority, of British engineers at that period.

In the 1890s, some forty years after the publication of the works of Nollau, Le Chatelier and Clark the balancing of locomotives, where it was carried out, was not always successfully achieved. Some contemporary evidence suggests that the attempt to apply design rules without an understanding of the underlying principles was not conducive to untroubled railway operation. Practice and theory were no longer in harmony. From the frequent letters arriving on the editorial desk at the offices of Engineering to a clear and unequivocal cry from the antipodes, the message was unmistakable.

> ...a careful examination of actual locomotives in various parts of Australia, and also of a large collection of photographs of locomotives by various English and American makers shows that, while many of them are balanced in a rational and intelligible way, others are either quite devoid of balance weights, or possess balance the magnitude and position of which cannot be reconciled with the principles of dynamics.[54]

The author of these words, Professor W.C. Kernot, presided over an inquiry, in 1893, during the course of which an investigation was carried out on some newly designed and built

six-coupled inside-cylinder locomotives that damaged the permanent way to the extent of actually fracturing the rails. Examination revealed that the engines carried no balance weights at all, the designer presumably considered that the outside coupling rods and their crank pins and bosses were sufficient to balance the inside cranks and their connections whereas balance weights of 200 lb. were needed. He also cited the case of an outside-cylinder locomotive which had been rebalanced and, as a consequence of an erroneous calculation, carried in each driving wheel a balance weight 300 lb. in excess of that required and reported the effects in the following terms:

> Running freely down along a steep grade the critical speed was exceeded; the driving wheels bounded along the rails, which were bent and broken in the most extraordinary way, as by blows of a gigantic hammer, the points of impact being situated at distances apart exactly equal to the circumference of the wheels. As the critical speed at which the wheels should begin to lift off the rails was only 48 miles per hour, while the actual speed, according to the finding of a board of inquiry, was 75, the wonder is, not that a long stretch of heavy railway was utterly disorganised, but that the engine and train escaped total destruction.[55]

Thus quite apart from the question of what percentage of the reciprocating masses of the locomotives it was appropriate to balance at the turn of the century, and it seems that this

matter was not seriously questioned, a simple and reliable method of evaluating the size and position of the balance weights was a desperate requirement.

11. Graphical Analysis

A third avenue of approach to the solution of a variety of engineering problems opened and was developed during the second half of the nineteenth century and that was the application of geometrical techniques as an alternative to mathematical analysis. For example, the velocity and the acceleration of a piston in the reciprocating engine mechanism could be found either analytically or geometrically. As has already been seen exact analytical expressions for the velocity and for the acceleration are complex and, from the beginning, were rarely used being replaced in practical design by simpler, and more easily manipulated, approximations. Theoretical exactitude is inherent in many of the graphical methods although, of course, the accuracy of the result is limited both by the accuracy with which the geometrical constructions can be drawn and scaled.[56] However, in many practical situations this limitation is not unacceptably serious because the results obtained are within reasonable working tolerances.

The application of geometrical methods to engineering problems was encouraged by the British Association for the Advancement of Science during the latter years of the nineteenth century and who indeed set up a committee for this purpose, whose first report was published in 1899.[57] Again, the use of graphical methods, although originating with the work of Gaspard

Monge[58] in the 1780s, was largely a development of the nineteenth century, significant work being done in France, Germany, Italy, Switzerland, as well as in Great Britain.[59] There were immediate and urgent practical problems to which graphics could be applied. Structural theory[60] advanced as civil engineers had to provide railway bridges[61] to carry large live loads over spans of unprecedented length; whilst the trend towards a more rational approach to machine design stimulated extensive activity in the field of kinematic analysis which culminated in some outstanding work and publications by A.B.W. Kennedy, Franz Reuleaux and R.H. Smith[62]

Where problems were amenable to solution either by simple mathematics or increasingly towards the end of the nineteenth century by graphical means, the graphical procedures were an attractive alternative to mathematical methods. Furthermore, the technique should have appealed to draughtsmen and engineers as a natural means of solving problems and also should have been within their level of competence. But it must be emphasised, graphical techniques - however convenient to use - also had their limitations the most serious of which was the fact that they did not, necessarily, promote an understanding of the nature of the problem involved. Their perfunctory, routine use was no guarantee of a successful conclusion.

12a. The Contribution of W.E. Dalby

It was within this general development and extension of graphics that the greatest contribution to balancing theory, since the fundamental basis was formulated at mid-century, was

made. And it was made by Professor W.E. Dalby. His semi-graphical method of determining the magnitude and position of the balance weights for a locomotive, for example, is a general geometrical solution of the balancing problem based upon the law that moments can be combined in the same way as forces. Its value, in Dalby's own opinion, was that it enabled a competent draughtsman to determine the balance weights for a complex system of masses about an engine crankshaft, with drawing-board, slide rule, accurate draughtsmanship and arithmetic. The value of the technique was enhanced because of the facility with which it could be checked and in the case of symmetrically arranged engines, such as the conventional steam locomotive it was self-checking.

Dalby's ideas were first presented in 1899 to the Institution of Naval Architects,[63] and this raises the question of cross-connections between the various branches of engineering at the end of the nineteenth century, when undoubtedly the matter of balancing engines and machinery generally was confronting engineers in many fields of endeavour. Actually, there is little evidence to suggest anything significant, and the reasons are not difficult to discern. In the first place the situations were vastly different, as a simple consideration of the role of the locomotive engineer compared with that of his marine counterpart will reveal. Essentially, the former was committed to attempting to satisfy insistent demands for ever more power with an established direct drive reciprocating mechanism and restricted by the severe limitations of track gauge (controlling the maximum diameter of inside cylinders) and

loading gauge (which put a constraint upon the size of outside cylinders). In other words, space was the major parameter. Economy of operation, however, was a more important factor for the marine engineer and so, without the same constrictions of space, compound engines became the norm and 'single-expansion' working developed into double-, triple- and even quadruple-expansion operation. Compound working involved engines with several cylinders, of different sizes and hence with reciprocating parts of different masses, thus affording the designer the opportunity to reduce the out-of-balance forces to a minimum. Internal combustion engines, of course, presented quite a new and separate state of affairs.[64]

Secondly, resulting from the accelerated rate of technological development and diversification during the second half of the nineteenth century engineering became more specialised and fragmented in organisation and, in the process, various groups became increasingly isolated from each other.[65] A natural consequence of this trend was a diminution in the opportunities for an exchange of information and ideas.

12b. 'The Balancing of Locomotives'

Although, as noted above, the scientific basis upon which Dalby's theories were founded was first published within the context of marine engineering and as we learn from his paper to the Naval Architects, it was prepared for that audience at the suggestion of Mr A.F. Yarrow.[66] The professor who by training was a railway engineer, from his academic position formulated a general method of solving balancing

problems which had wide application and has been taught and used throughout the twentieth century or, as he himself has written,

> The method has found wide acceptance, is now used in all parts of the world, and has found its way into textbooks with and without acknowledgement.[67]

On 15 November 1901, Dalby presented his paper 'The Balancing of Locomotives'[68] to a large audience of some three hundred people at the Institution of Mechanical Engineers and in doing so offered to locomotive engineers a comprehensive means of accomplishing the necessary task which recent operating experience had revealed to be inadequately carried out. In one important respect his paper also marked a significant advance on the thinking of half a century earlier because it stated that one of its objectives was a consideration of the effect of the counterweights on the track. At last, in the enunciation of a theory of balancing there was an explicit recognition that machine and track were complementary components in a single system.

In the event, as the following pages will show, Dalby did not pursue this topic in any depth. Nor did the revelations of Goss, at Purdue, appear to stimulate much interest amongst locomotive men although, of course, it must be conceded that he was interested in vehicle behaviour rather than railway track. The failure of the 'systems' approach to the subject is probably best accounted for the following terms. The existence of so many badly balanced locomotives during the second half of the

nineteenth century and, indeed, into the twentieth century indicates a lack of understanding of the dynamics of the locomotive itself. And this deficiency precluded a proper appreciation of the significance of the dynamic interaction of vehicle and track. Engineers concerned themselves with the issue meaningfully when circumstances compelled them to do so. As will be shown in Chapter 6, it was only when the deterioration of bridges became a matter of grave concern that the subject was taken seriously and then the initiative came from civil, rather than locomotive, engineers.

Before moving on to a consideration of Dalby's paper and his method of carrying out balancing calculations it is necessary to appreciate what he meant by 'balancing' and to recognise that his definition marked no advance on the ideas of Nollau, Le Chatelier and Clark. His approach to the problem is stated in Article 7 of his paper:

> The moving masses in an engine may be divided into those which revolve with the crank shaft, and those which the crank shaft reciprocates. The preceding principles [Articles 2 to 6, inclusive, of the paper summarise the fundamental ideas of his method as detailed in his paper to the Institution of Naval Architects] applying to revolving mass may be made to apply to the reciprocating masses. It is only necessary to suppose that the reciprocating masses are transferred to their respective crank-pins, and to treat them there as a separate revolving system, the balance weights

> found being those which when reciprocated will balance the reciprocating masses. This method of treatment really assumes an infinitely long connecting-rod so that the solution obtained for ordinary rods is only approximate. The error involved is however negligible in locomotive work. Again in locomotive work it is almost the universal custom to balance the reciprocating masses by revolving masses placed in the wheels, the actual balance weight in a wheel being the resultant of the balance weights required for the revolving and reciprocating parts respectively. There is therefore no need to discriminate between the revolving and reciprocating parts in the process of finding the balance weights. Having settled how much of the reciprocating parts it is desirable to balance, include it with the revolving masses at the crank-pin, and consider the whole as a revolving system.[69]

Thus the underlying assumptions and aims are identical with those made half a century earlier. There is a tacit acknowledgement that there could be a method of balancing the reciprocating masses by means other than revolving masses in the driving wheels although the matter is not pursued. Clearly Dalby was attempting to cope with contemporary locomotive practice accepting current ideas and limitations without either attempting to improve or to modify them. Indeed, he seems not to have questioned them. At the very best his method offered the possibility of performing successfully what a number of

engineers were unsuccessfully trying to do. And that was, to get a balance weight of the right size (based on their assumptions of percentage of reciprocating masses to be compensated) in the right place. Judged from this point of view his method must be recognised as a major contribution to better balancing practice.

Details of Dalby's semi-graphical method of balancing with an illustrative example of its use are given in Appendix 2.

12.c The Adoption of Dalby's Method

Professor Dalby's method, as he claimed, depended ultimately on no more than accurate drawing and simple arithmetic. Within the context of balancing a locomotive it was an elegant partial solution to the problem. 'Partial' because its use required the pre-determination, or the assumption, of the proportion of reciprocating masses to be balanced. On this, the most critical aspect of the exercise, it offered no assistance. Nevertheless, in the circumstances in which it was published it could have been expected that it would have found a ready and enthusiastic acceptance and widespread use but the scanty evidence that survives suggests that the case was otherwise.

The two Great Western Railway 'Balance Weight' books, covering the period 1910-1924, held at the National Railway Museum, in York, reveal that throughout this period one of the major railway companies of this country - and, indeed, one generally regarded as being progressive - adhered to the old multi-calculating methods. In the absence of far more contemporary design documents it is obviously impossible to

generalise about the adoption of the semi-graphical method although it does not seem unreasonable to suppose that the situation on the GWR was not much different from that in design offices elsewhere. Other evidence, based on the recollections of engineers engaged in locomotive design during the 1920s indicates that it was towards the end of that decade before the method really penetrated into the design offices of railway companies and locomotive builders. According to Brian Reed, Dalby's methods were used on the Southern Railway from the formation of that company and they were also used by the LMS railway and by the North British Locomotive Company for the 'Royal Scots' in 1927, 'but my memory is that it had not been used much by N.B.L. before that'.[70] This tends to be corroborated by O.S. Nock who wrote,

> The extent to which 'rule of thumb' methods and guesswork prevailed in locomotive drawing offices was quite incredible, even at places like Swindon and Crewe; and it was not until the time of the Bridge Stress Committee that bridge and locomotive engineers really got down to the problems of balancing in anything like a scientific way.[71]

The few British Railways' drawings of the 1950s, from the drawing offices at Brighton and Doncaster indicate that the graphical approach was generally applied then. Thus it seems that within the field of locomotive engineering it took between a quarter and a half a century for a simple, sound and practical

method of carrying out balancing calculations to come into general use. In seeking to explain the apparent tardiness in adopting it two possible reasons come to mind, first a lack of information and secondly a conservative attitude on the part of those responsible for design. Inadequate information is a hypothesis that can hardly be sustained because shortly after Dalby's paper to the Institution of Mechanical Engineers, the first edition of his book The Balancing of Engines[72] was published, and this was followed by a second edition in 1906. In the following year, another book on the subject, by Archibald Sharp, was also published in London.[73] And then, in 1917, the third edition of Dalby's book, which by that time had obviously established itself as the standard work on the subject, appeared.

A real demand for the book during the first twenty years of the present century is indicated by the provision of three separate editions in a period of fifteen years and this in itself provides convincing testimony that scarcity of knowledge was not a significant contributory factor. It is not suggested by this argument, of course, that the demand for the work was entirely, or even largely, from locomotive engineers but it would be unrealistic to suppose that, as a group, they were unaware of its existence or of the possibility that it might have something to offer them. But this thought, perhaps, would occur only to the curious or to those so dissatisfied with the existing situation that an alternative method was being actively sought.

More tenable is the notion of conservatism, a thesis

sustained by the delay of about twenty five years noted in the preceding paragraph. Probably the main reason why Dalby's method was not more widely adopted earlier was because those in authority, that is those charged with responsibility for initiating changes of procedure, were reluctant to abandon their customary methods if these had given reasonable satisfaction. Hesitancy on the part of a busy chief mechanical engineer, preoccupied with multifarious matters and problems associated with the operation and maintenance of a large locomotive stud in addition to intermittent involvement in design and so on, in making a swift transition to new practices is understandable. The adjective 'new' is, or may be, of tremendous consequence here because in seeking a plausible explanation for the seemingly undue delay in accepting the semi-graphical solution there is a distinct possibility that one can either overlook or under-rate the difficulties involved for those making the departure from traditional practices. Today, looking back to the early decades of this century and comparing the vectorial method with the earlier multi-calculation process the former is considered immeasurably superior because in addition to its simplicity, it is a quicker process and provides fewer opportunities for error. But the engineer who makes this assessment is likely, almost certainly, through his education and training to be accustomed to vector methods. Equally, it is most unlikely that senior engineers at the time in question were familiar with them. A glance at the first chapter or two of either Dalby's or Sharp's books will give an idea of these difficulties. They introduced a new vocabulary, the distinction

between scalar and vector quantities, the manipulation of vectors, the vectorial representation of couples, and associated sign conventions. In fact before it could commend itself or make a ready appeal, new concepts and a new terminology had to be assimilated. Albeit no more than a conjecture it is not unreasonable to suppose that those who studied these books in the years prior to the grouping of the railways were responsible for the introduction of the vectorial methods from the mid-1920s onwards.

Earlier it has been stated that Professor Dalby's method provided a partial solution to the problem of balancing a locomotive. He appears never to have seriously considered how much of the reciprocating masses should be balanced and in Article 7 of his paper quoted above he merely stated, 'Having settled how much of the reciprocating parts it is desirable to balance...' without comment or any indication of how such settlement was achieved. In his illustrative examples of Lancashire and Yorkshire engines he introduces his consideration with the statement 'Following a usual custom two-thirds of the reciprocating masses are balanced in each case.'[74] In the discussion following the reading of this paper some surprise was expressed that no data was provided to permit a determination of the percentage of reciprocating weights to be balanced.[75] Acknowledging that two-thirds was generally accepted as good practice, Mr J. Fraser Masterton pointed out that whilst this might be sufficient in one class of engine, in another class it might be too much. At the turn of the century this was the crux of the matter. What percentage of the reciprocating weights

should be balanced?

According to M.C. Duffy this became a subject of great controversy.[76] But there is no real evidence that the issue was one of much concern around 1900, and certainly Dalby himself had no clear quantitative ideas on the topic. His philosophy on this, expressed in a communication on his paper, was that as much as possible of the reciprocating parts should be balanced.

> But since in a two-cylinder engine whatever was balanced horizontally only appeared again vertically in the form of a hammer-blow, the proportion must not be greater than that required to keep the hammer-blow within reasonable limits for the sake of the bridges and the permanent way, and to be sure that there was no danger of the balance weight lifting the wheel clear of the rail at high speeds. In a four-cylinder engine undoubtedly the proper answer was - balance all the reciprocating parts completely.[77]

Opinions on the appropriate percentage to be balanced were personal and varied from one extreme to the other. Whereas Professor Unwin thought that none of the reciprocating weights should be balanced Professors Perry and Rankine considered that they should be balanced entirely.[78] Ultimately, in actual practice it resulted in a dependence on individual judgement on the part of a locomotive superintendent which in turn was based upon steadiness of running. Interaction between engine and track was not perceived as a significant factor.

As the steam locomotive entered the twentieth century, then, there was in the almost unquestioning adherence to the Le Chatelier-Clark recommendations, an unwarranted degree of over-balance.

13a. Locomotive Testing

The stability and riding characteristics of a locomotive were obviously affected by the imperfections of the permanent way over which it ran.[79] By suspending the engine under test with its wheels clear of the track Nollau, Le Chatelier and Clark eliminated this external source of disturbance. In this early example of 'controlling' the test by isolating the machine under investigation from extraneous influences and sources of error these workers demonstrated the value of a 'scientific' approach to the problem and pointed to the potential value of a testing station where the many aspects of a locomotive could be methodically examined. However, forty years were to pass before such stations were erected and even then the initiative was not taken by the railway industry.

A special plant which could accommodate a locomotive in working condition, whilst remaining stationary, together with the associated equipment and instrumentation to record and evaluate the results possessed a number of distinct advantages. The behaviour of individual components could be examined under pre-determined and controlled conditions, leading to the possibility of rationalising design proportions and to better future designs. Specific problems, or the effect of alterations could be investigated as well as carrying out general

performance and efficiency tests.

Aware of the benefits derived from the methodical testing of stationary steam engines in plants established for the purpose, it was Purdue University, an academic institution not well endowed either with funds or with personnel experienced in locomotive technology, which perceived the advantages to be gained from an engineering laboratory devoted to the study of locomotive performance.[80] With the cooperation of a locomotive manufacturer who provided an engine, typical of good contemporary practice, for the small sum of money available, this university opened the first[81] locomotive testing plant in the world in 1891.[82] To the advantages described above could be added those of the education of students in locomotive engineering and the facilities for research.

13b. The Work of W.F. Goss at Purdue

During the academic year 1891-2, the first series of tests was carried out under the direction of W.F.M. Goss. These were mainly low-power efficiency tests but the work did include an investigation of balancing. The results of the latter were presented to the American Society of Mechanical Engineers in December 1894, being included in Vol.XVI of their Transactions. Likewise, results of other tests were published as work progressed and hence the influence of Goss and the work at Purdue was immediate and extended to Europe. This process was given impetus in 1907 when a number of papers, originating in these researches, was collected and published in a single volume.[83]

Concern with the increasing seriousness of the consequences - 'Heavy rails have been kinked, and bridges have been shaken to their fall' - of running overbalanced locomotives at high speeds is indicated by the fact that this topic was selected for investigation in the first year of operation of the laboratory. The object of the experiment was to demonstrate the

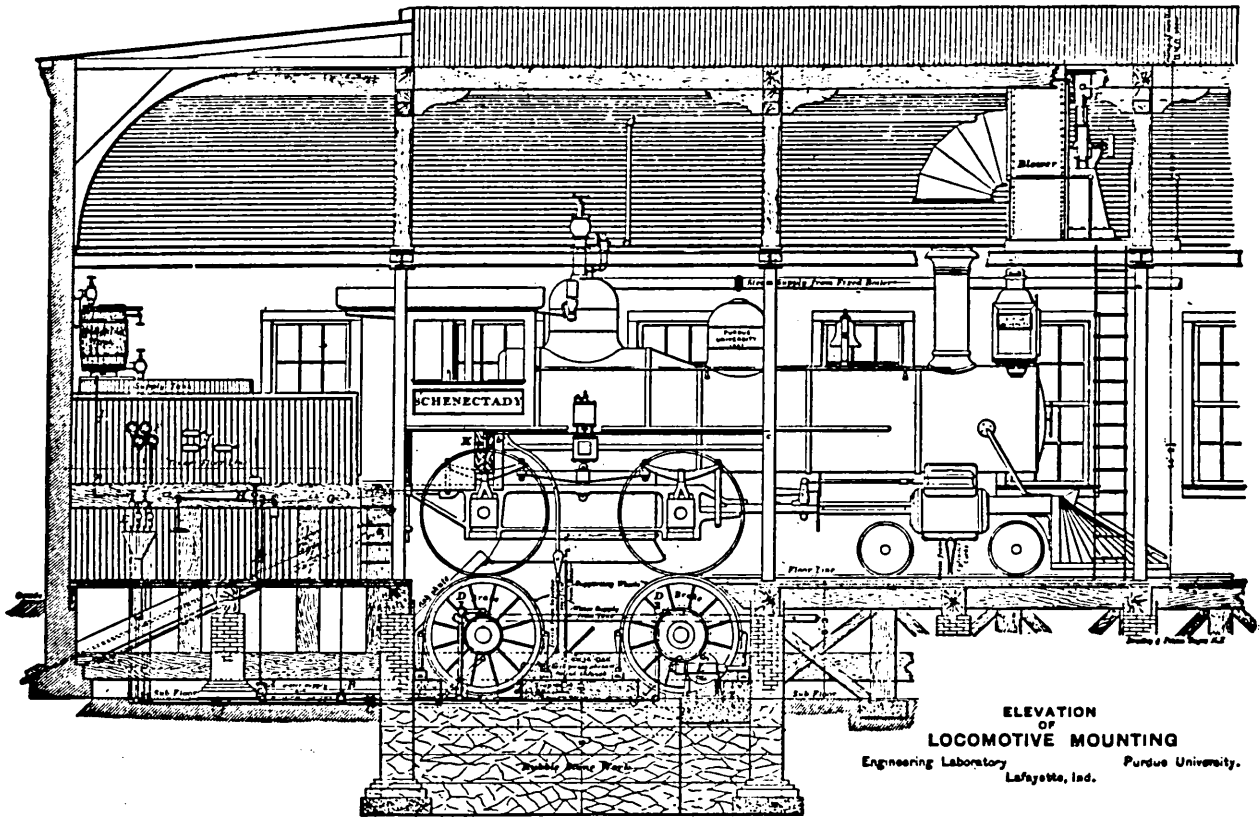


Fig.3.13 The Locomotive 'Schenectady' in the Engineering Laboratory, Purdue University

variation in pressure between the driving wheels and the rail and to determine whether the drivers would actually lift from the track at speeds likely to be attained in service. This was to be accomplished by the ingenious technique of passing a small-diameter wire beneath the revolving wheel. Variation in pressure being registered by the resulting varying thickness of the wire whilst actual wheel lift would be revealed by sections of the test wire retaining its full diameter.[84]

An 'American' type 4-4-0 locomotive Schenectady, supplied by the Schenectady Locomotive Works, weighing nearly 40 tons, was used for the tests (see Fig.3.13)[85]

Straight lengths of annealed iron wire, 0.037 inch in diameter and weighing about one ounce (per length of 20ft) were used. The wire which was to be passed under the driver was guided by a length of 3/8 inch gas pipe fixed to the laboratory floor in front of each driver as shown in the diagram (Fig.3.14),[86] and apart from a plate fixed behind the front driving wheel to deflect the wire passing under it away from the rear driver the passage of the wire was uncontrolled after it left the wheel.

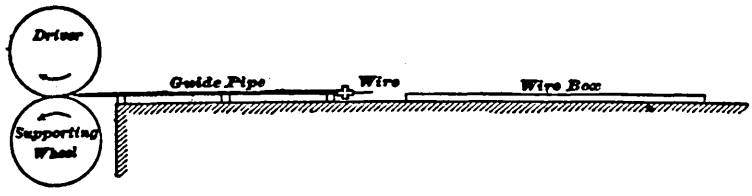


Fig.3.14 Arrangement for feeding lengths of iron wire beneath the driving wheels of the locomotive

A permanent record of the engine's speed was given by a speed recorder and by means of cuts made across the face of each driving wheel a correlation was obtained between the movement of the wheel and its effect on the wire.

Careful measurements were made at five-inch intervals along the test wires, the results plotted and a smooth curve drawn through the points, to give graphs such as the following Figs.3.15 and 3.16 taken from Goss's paper, Fig.200 and Fig.201.[87] The small circles indicate the actual thickness of the wire.

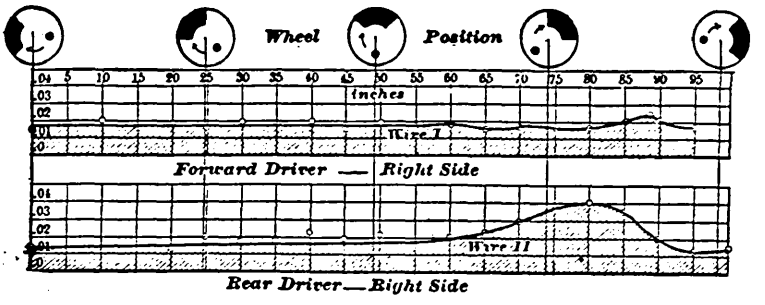


FIG. 200.

Fig.3.15
Graph showing wire deformation

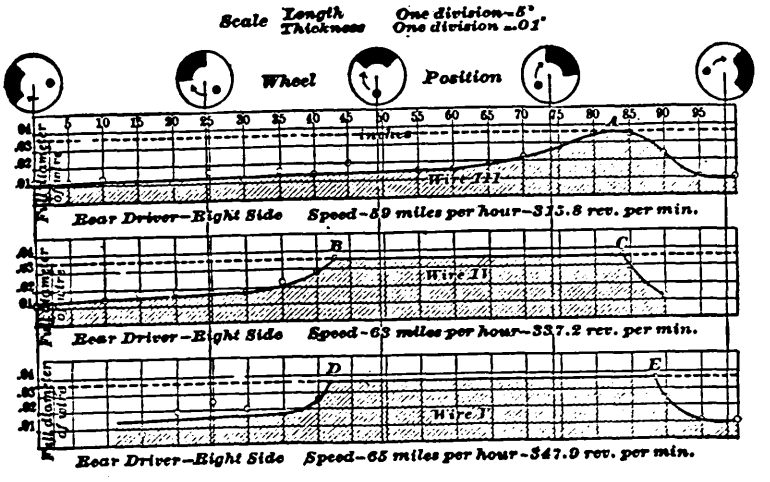

Scale Length One division=5'
Thickness One division=.01'
Wheel
Position
inches
Wire III
Rear Driver—Right Side Speed-59 miles per hour-315.8 rev. per min.
Wire II
Rear Driver—Right Side Speed-63 miles per hour-337.2 rev. per min.
Wire I
Rear Driver—Right Side Speed-65 miles per hour-347.9 rev. per min.

FIG. 201.

Fig.3.16
Graph illustrating lack of contact between wheel and rail

Besides showing to a greater or lesser extent what they set out to demonstrate these tests also revealed several other important characteristics of the interaction between wheel and rail at high speeds. Prior to their commencement the engine was rebalanced, by the addition of further weights, to achieve a complete horizontal balance and thus increase its steadiness on the rollers in the laboratory. A consequence of this was that the rear drivers were overbalanced to a degree that would not have been permitted in good practice although, tellingly, Goss comments that this condition was not rare.[88] Comparison of the two graphs (Fig.3.15) clearly shows the greater variation in wire thickness (Wire II) due to the excess in this wheel. The second diagram (Fig.3.16) (Wire IV) indicates that between points B and C there is no contact between wheel and rail for a distance of about 40 inches; the wire passing between them without deformation. Not so obvious but nevertheless not unimportant is the destructive effect of the variation in wheel loading even when this was insufficient to cause the rise of the wheel from the rail. The parts of the wires not included in the graphs did not show much variation in thickness because, as stated in the paper, they were rolled so thin by the normal contact pressure that further increments in pressure made little difference.

Quite apart from the effects of the balance weights on the motion of a wheel on a rail these tests clearly indicated the influence of other disturbing factors, that is, vibrations. Three different classes of vibrations were identified:

1. The rocking of the locomotive on its springs which tended to vary the contact pressure between wheel and rail independently of the effect of the balance weight and which could augment, reduce, or alter in a complex manner the action of the counterbalance. This phenomenon made it impossible to duplicate test wires even under conditions of constant speed and added to the difficulties of predicting wheel behaviour whether based upon experimental or analytical considerations.
2. Vibration of the wheel as a whole revealed by an alternate increase and decrease in the thickness of the wire at successive measuring points (see Fig.3.15, Wires I and II). The amplitude of these vibrations was small and Goss, not unreasonably, conjectures as his only reference to their origin the process of introducing the test wires, although he admits that the experiment does not show any connection.

A suddenly applied load, such as the feeding of the wire between wheel and roller, would certainly induce a transient vibration into the system under examination and whilst on the one hand this may be considered undesirable since it introduced an extraneous factor into the investigation, on the other hand, it might give some appreciation of the effect of rail joints, points, and imperfections in the permanent way as a continuous, and potentially more dangerous, source of random vibrations.

3. At high rotational speeds of the driving wheel the single mark cut across its face, made two projections on the wire, separated by about 1/8 inch - and representing a time interval of about 8 ms, indicating that after making one impression the tyre momentarily lost contact with the wire before making the second impression. Contact of the turning wheel with the rail, even in the region of maximum contact pressure, was not continuous but a succession of impacts. These vibrations which affected only the region of contact of wheel and rail, and not the whole wheel, were due to the elasticity of the interacting components.

To summarise, then, Professor Goss had shown that whilst locomotives balanced according to the usual rules, that is, all the revolving parts and from 40 to 80 per cent of the reciprocating parts, were not likely to be derailed because of the action of the balance weights, unless the speed was excessive; badly overbalanced engines could be expected to leave the track. A wheel caused to lift from the rail by the action of its counter-balance rose comparatively slowly and descended rapidly, its maximum rise occurring after the balance weight had passed its highest point. The tendency of the counterbalance to lift the wheel could either be assisted or opposed by the movement of the locomotive on its springs and, perhaps most startlingly, the contact between wheel and rail at high speeds was a series of impacts rather than continuous.[89]

These conclusions clearly revealed that the interaction

between wheel and track was far more complex than analyses based upon rigid-body dynamics indicated. Sinusoidal curves portraying a rhythmic variation of contact pressure throughout each revolution of the driving wheel although, maybe, a not unreasonable first approximation hardly represented reality. And the consequences for the rails were serious but generally unacknowledged by locomotive engineers.

The findings of Goss, obtainable only from a careful investigation such as he performed, permit us to comprehend why other engineers, both his predecessors and his contemporaries, lacked an appreciation of the true nature of the interaction between vehicle and track.

13c. Other Views

In discussing this matter and its effect upon the engine Clark's assessment of the situation was:

> The downward pressure is met by the rails, and the stability can be affected only by the upward pressure, when it exceeds the weight of the wheels and axles and the mounting, for otherwise the springs cannot be affected.[90]

Pursuing his argument and considering the situation in which there could be a resultant force acting on the springs which 'could not affect the compass of the spring materially above 1/8 inch' he concluded that this was insignificant and

confirmed in practice.

With a consideration of the effect of the balance weights on the permanent way as one of his objectives Professor Dalby did not carry the matter much further and his view neglects the implications of the elasticity of constructional materials. He wrote:

> The variation of the pressure between the wheel and the rail, caused by the vertical component of the centrifugal force due to the part of the balance weight concerned in balancing the reciprocating masses, is called the 'hammer blow'. This description of the effect does not describe what takes place very well, because the variation of the pressure is not sudden, but continuous, except in the extreme case where the maximum value of the variation is greater than the weight on the wheel; in which case the wheel lifts for an instant, and coming down again gives the rail a true blow.[91]

In small-wheeled, coupled goods engines, the extreme cases were not entirely unknown in practice. However, of more general significance from the point of view of locomotive performance was the possibility of wheel slip if the variation of contact pressure exceeded certain limits, the likelihood of this being greatest in 'single' engines. Dalby's graph showing the variation in rail pressure for the Lancashire and Yorkshire Railway engine considered above is given below, Fig.3.17.[92]

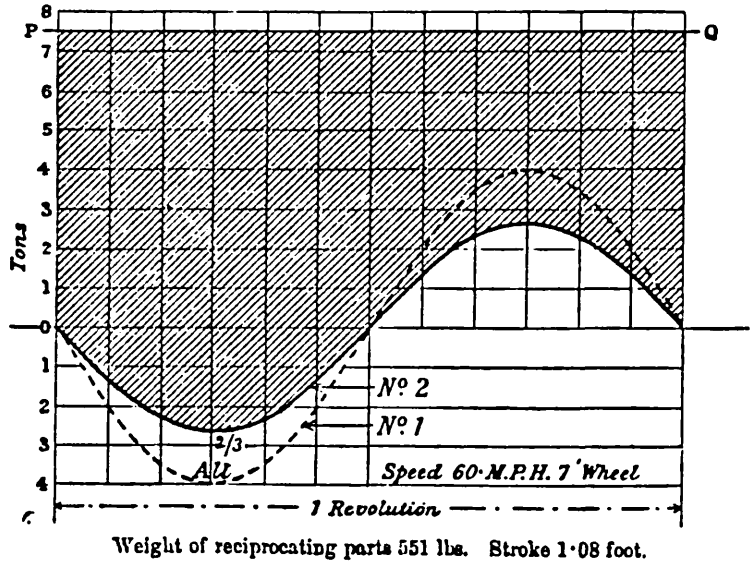


Fig.3.17 W.E. Dalby's graph showing variation in wheel-rail contact force for an Inside Cylinder Single Engine

The incidence of wheel slip could be detected from a comparison of the torque on the crank axle with the couple resisting slipping, in fact it occurred when these two effects were equal. The resisting couple itself varied directly with the magnitude of the contact pressure. This tendency was also illustrated in a combined graph of average crank effort and couple resisting slipping for a four-coupled bogie express passenger engine of the same railway, Fig.3.18.[93]

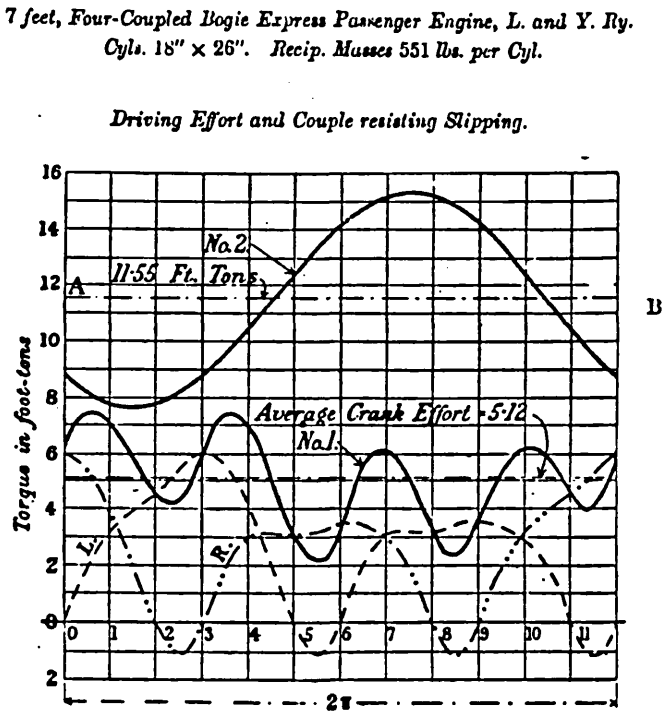

7 feet, Four-Coupled Bogie Express Passenger Engine, L. and Y. Ry.
Cyls. 18" x 26". Recip. Masses 551 lbs. per Cyl.
Driving Effort and Couple resisting Slipping.
Torque in foot-tons
No.2
11·55 Ft. Tons
A
B
Average Crank Effort 5·12
No.1
0 1 2 3 4 5 6 7 8 9 10 11 12

Fig.3.18 W.E. Dalby's graph comparing driving torque with the couple resisting slipping for an express passenger engine.

It can be seen from this diagram that for crank position 1 the curves Nos.1 and 2 come close together. A coincidence or intersection of two such curves for a 'single driver' engine would result in slipping although in this particular case the effect of the coupled wheels would prevent it.

Wheel slip, with the possible consequent hazard of track damage, was also to be avoided because it subjected the crank-shaft to undesirable torsional strain, induced by a reduction in tyre-rail contact pressure on the wheel tending to lift with an accompanying increase in wheel contact pressure on the other, non-slipping, side of the locomotive. In the extreme case of actual wheel lift this transmitted the torque from both cranks

to the wheel without slip. As a result of these considerations he concluded that for a 'single' engine the greatest proportion of reciprocating masses that should be balanced was 'about two-thirds'.[94] In the case of 'coupled' locomotives, the variation of rail pressure was achieved by dividing the balance weight used, to balance the reciprocating masses, between the coupled wheels.[95]

So far as future work was concerned the reference to 'singles' was hardly pertinent except, perhaps, with reference to the re-balancing of existing stock, because as a type its usefulness had already been surpassed in the nineteenth century. And his treatment of coupled locomotives, indeed all future construction, was - as has been noted above - to divide the reciprocating balance:

> This is unquestionably the best way to deal with whatever proportion of the reciprocating masses is balanced, so far as the permanent way is concerned; and with regard to the variation of tractive effort, the whole of the reciprocating masses may be balanced without introducing too great a variation of rail pressure.[96]

Although these words, written at the end of an illustrative example, may be intended to refer to a specific locomotive, the sentence itself has the form of a generalisation and, as such, can scarcely be accepted as a recommendation conducive to future successful balancing practice.

Professor Dalby's treatment postulated a simple relationship between wheel and rail and apart from his brief reference to the beneficial effect on the track of dividing the reciprocating balance weight between the coupled wheels, the permanent way, as such, did not receive any serious attention. The possible results of wheel bounce, or excessive slip, or a combination of both was not recognised. Neither in his paper, delivered almost seven years after the publication of Goss's work at Purdue, nor in any edition of his book did he make reference to the fundamentally important investigation carried out in the United States of America. It must be conceded that Goss and his co-workers did not concern themselves with the track either.

At the beginning of the present century, then, although the complexity of the wheel-track interaction had been identified and partially revealed at least as a subject warranting further and closer attention it did not receive it. Undoubtedly, the major reason for this was the organisation of railway engineering into separate and virtually autonomous spheres of responsibility. Whilst the locomotives and rolling stock were the concern of the locomotive superintendent or the chief mechanical engineer, the track together with bridges and buildings came under the jurisdiction of the civil engineer. At the crucial point of contact, the wheels upon the rails, there was nobody with a meaningful overall responsibility. Undoubtedly there was a general awareness amongst locomotive engineers that for the sake of the track and underline bridges the hammer-blow effect should not be excessive. Additionally

they believed, or at least worked on the assumption, that this would be contained within acceptable limits provided that the percentage of reciprocating masses balanced conformed to the norm, i.e. about sixty-six per cent.

Similarly, civil engineers were satisfied with information on the dimensions of wheel bases and provided specified static axle loads were not exceeded.

This procedure although well-established and tolerated during the nineteenth century led to a worsening situation in the first twenty years of the twentieth century and was shown by the Bridge Stress Committee to be quite inadequate.[97]

14. Final Comments

Once the desirability of balancing locomotives had been established, it might have been expected that Railway companies would quickly adopt the practice since the results of both Le Chatelier's and Clark's experiments had conclusively demonstrated not only improved steadiness of motion at speed, significant from the point of view of safety, but also an economy of coal consumption. Indeed, Clark's trials on the 'Canute', one of Joseph Beattie's 6ft 6in 'singles' on the London and South Western Railway achieved a substantial saving in coal - estimated to be about 20 per cent. He also claimed that some of his outside-cylinder 2-4-0 freight engines, which were rebalanced at the same period, produced fuel savings of 11 per cent.[98]

Although fuel costs for locomotives were but a small

part of the overall costs of operating a railway, and any economy achieved was not really significant, the topic was one of continuing interest and consideration and was deemed worthy by Clark to be emphasised as an advantage of balancing. Arising from this is the question of why the whole LSWR locomotive stud, and indeed the locomotives of the whole country were not immediately rebalanced, but they were not. Clark himself noted the imperfect state of balance of the locomotive stock of the country and as the preceding pages have shown this unsatisfactory situation persisted throughout the remaining years of the nineteenth century. However, following Clark's work, locomotive balancing was gradually extended but it was of an irregular character and ranged from a competent accomplishment through unsuccessful attempts to complete omission.

In attempting to understand this, the possibility must be acknowledged that confronted with the need for economy in the operation of existing locomotive stock, superintendents could not secure the necessary finance for these modifications from boards of directors. Especially would this be likely to be the case with engines whose operating performance was satisfactory and relatively trouble-free. On the other hand locomotives in the course of construction or new designs for future service would, in general, almost certainly incorporate some degree of reciprocating balance, probably in accordance with the rules laid down by Clark.

Another, and perhaps more significant impediment to the implementation of a universal balancing policy, was

consideration of the strength of the track. The 'overbalance' required for the reciprocating masses was likely to cause a more-or-less serious hammer-blow on the rails, depending on the weight and state of the track and the speed of the engine. It has been stated by an earlier commentator on the subject that for this reason many single driving wheel type of passenger engines were balanced for the revolving masses only, while some four-coupled locomotives, even of the same type and class, were balanced for reciprocating masses and others were not.[99] It is not unreasonable to conjecture that the basis for this variation in treatment followed from a consideration of the running requirements and route allocation of the individual engines.

A revealing aspect of the overall scene during the period here considered is the absence of any serious recognition of the interaction between the locomotive and the track on which it ran. Michael Duffy, in his 'Stephenson Bicentenary Address' accords Stephenson the honour of being an early exponent of the 'systems' approach[100] (in the modern sense of the expression) with his locomotive-track combination although it seems not unreasonable, if such credit is to be given, to bestow it upon Richard Trevithick who indisputably had priority in running a steam locomotive on a track. Both had the experience of building a locomotive which destroyed the track. Certainly during the second half of the nineteenth century the evidence does not suggest a 'systems' treatment of the problems of railway engineering, indeed the die was cast for almost the opposite approach. With the rapid growth of the railway network it became necessary to divide responsibilities within the

various companies and so responsibility for motive power and rolling stock became separated from that for the permanent way. Such organisation led to increased specialisation and physical separation of various departments which increased the problems of communication and cooperation and in the absence of effective management, sometimes led to direct conflict between civil and mechanical engineering departments. Incidents of this sort occurred well into the present century. Apart from not possessing authority or responsbility in connection with the permanent way locomotive superintendents (and in the twentieth century - chief mechanical engineers) had sufficient problems with keeping their locomotive studs in action, building new engines and providing new designs for ever more powerful machines, without concerning themselves unduly about the track. The demand for greater power in general necessitated heavier locomotives which in turn required heavier track, and this was the unmistakable trend, all called for considerable expenditure which frequently directors were reluctant to sanction. The conflicting requirements of the various departments were, in themselves, not conducive to harmonious relationships between them.

Of the numerous diverse problems confronting the locomotive engineer during this period none could have been greater or more significant than the simultaneous transformation in methods of production and transition in materials of construction.

If locomotive superintendents were not particularly preoccupied with balancing as such, and on the available evidence it seems that they were not, it is probably because they were engaged on matters of a larger scale as just suggested.

References and Notes

1. Report of the Gauge Commissioners. Presented to both Houses of Parliament by Command of Her Majesty. Printed by T.R. Harrison, London, 1846.
2. Ibid., Question No.4294.
3. Ibid., Question No.4295.
4. Ibid., Question No.4297.
5. Nollau, H., 'Eisenbahn Betriebsmittel', Eisenbahn Zeitung, (Stuttgart), 1848, pp.323-4.
6. Ibid., p.323.
7. The generous springing and upholstery introduced in the seats of first and second class railway carriages for the function of insulating passengers from the vibration and jolts of this mode of travel is thought to have had a direct influence on the design of late nineteenth-century domestic furniture (see Wolfgang Schivelbusch, The Railway Journey, pp.123-125).
8. Through private correspondence, I have been informed by Prof.Dr-Ing. K. Mauel, of Verein Deutscher Ingenieure, that the "maschinenmeister" of a railway company, generally, was not responsible for either design or building of locomotives.
9. Nollau, op.cit., p.323, equation I.

10. Nollau uses the term 'piston-rod' rather than 'connecting-rod. Acknowledgement is made here to Mr T. Summers, BSc, for translating H. Nollau's paper into English and for his assistance with German language material.

11. The connecting-rod was also dealt with by a rule-of-thumb apportionment of its total weight between its two ends. Sometimes this was equally divided but more frequently, one third of the weight was regarded as reciprocating and two-thirds as rotating. However, it seems that Nollau initiated a practice which has been employed almost generally ever since in balancing problems - that of treating the connecting-rod as two point masses.

12. Nollau, op.cit., p.323.

13. The Engineer, 18 April 1856, pp.214-215.

14. Nollau, op.cit., p.324, equation II.

15. Ibid., p.324, equation III.

16. Ibid., p.324. The weights and measures quoted here and taken from Nollau's paper, are expressed in Prussian units. The relationship between the English and Prussian units of length and weight is:

1 foot (English) = 0.97113 foot (Prussian)

1 lb Avoirdupois = 0.9665577 lb (Prussian)

These equivalents are taken from C. von Oeynhausen and H. von Dechen, Railways in England 1826 and 1827, The Newcomen Society, 1971, p.3.

17. McConnell, J.E., 'On the Balancing of Wheels', Proceedings of the Institution of Mechanical Engineers, 13 June, 1848, p.6.

18. Nollau, op.cit., p.324.

19. Duffy, M.C., 'Mechanics, thermodynamics and locomotive design: analytical methods and the classic form', History and Technology, Vol.2, No.1, 1985, p.37.

20. Enquiries to the Deutsche Museum, München, the Deutsche Gesellschaft für Eisenbahn-Geschiete e.V. Heilbronn, and the Verein Deutscher Ingenieure, Düsseldorf have not been successful in revealing any biographical information about H. Nollau.

21. Private correspondence.

22. Le Chatelier, L., Etudes sur la Stabilité des Machines Locomotives en Mouvement, Librairie Scientifique-Industrielle de L. Mathiar (Augustin), Paris, 1849.

23. Op.cit., Fig.6.

24. Op.cit., pp.94-99.

25. Le Chatelier defined the parasitic motions of the locomotive generated by the mechanism as

    i) mouvement de lacet - nosing

    ii) mouvement de galop - pitching

    iii) mouvement de roulis - rolling

    iv) mouvement de tangage - variation in draw-bar pull

26. Op.cit., p.16, equation 10.

27. Op.cit., p.18, equation 11.

28. Nollau, op.cit., p.324.

29. Le Chatelier, op.cit., pp.18-19.

30. Bevan, Thomas, The Theory of Machines, Longmans, London, 1948, p.86.

31. Clark, D.K., Railway Locomotives: Their Progress, Mechanical Construction and Performance with the Recent Practice in England and America, Blackie and Son, Glasgow, 1860, Introductory Preface, p.viii.

32. Op.cit., p.166.

33. Op.cit., p.168.

34. Op.cit., p.167, Table LXXXVI.

35. Le Chatelier, op.cit., p.21, equation 20, which gives the resultant nosing couple.

36. Clark, op.cit., p.170, Fig.192.

37. Op.cit., p.179.

38. Op.cit., p.179.

39. Terminology.

The early workers in any field are obviously confronted with the problems of communicating their ideas and findings and of necessity must frequently devise their own terminology. Inherent in this practice is the probability that different expressions will be applied to the same phenomenon or feature. This confusing situation could be, and was, further worsened if a single worker, for variation or literary effect, chose to employ different words for the same thing. For example, a writer (The Engineer, 15 February 1856, p.75, Author 'C') on the topic of 'Horizontal Oscillation' in

locomotives used no fewer than four different nouns in a short article to designate 'balance-weights' and while this may not have troubled the knowledgeable it was hardly conducive to the enlightenment of the uninitiated. The pedagogic value of much writing at this period was diminished by the rather loose use of technical terms. Thus Fernihough, in explaining his theory to the Gauge Commissioners (Section 1 of this chapter), did not draw any distinction between 'force' and 'pressure' and used the words synonymously. In similar vein he referred to equating centrifugal force to 'momentum' or 'inertia' and quite clearly, in his mind at least, these were not concepts with precise and different meanings.

Although, in general, a more-or-less uniform terminology did evolve in this field of work in some instances it lacked precision as, for example, the application of the expression 'hammer-blow' to describe the variation in wheel-track contact pressure. Additionally, anomalies remained well into the twentieth century because of adherence to old-established phraseology. In American railway engineering language 'cross-balancing' was called 'dynamic balancing' to distinguish it from 'static balancing', or balancing without compensation for the couples introduced by the insertion of weights into the wheels despite the fact that in balancing operations generally the term 'static-balancing' possessed a somewhat different

meaning. Indeed, because a true balance of the machine, or anything approaching real equilibration of the motion parts, was not even attempted it was a misnomer to call the exercise 'balancing' but with this title it remained a topic for discussion and debate in the railway world throughout the life of the reciprocating steam locomotive.

A study of the evolution of technical vocabulary and its contribution to the development of industrial and scientific endeavour at this period seems to be a worthwhile and illuminating activity, with the potential of assisting our understanding of the emergence and growth of the 'engineering sciences', but one which, as yet, does not appear to have been undertaken by the historian of technology. Undoubtedly, the nebulous vocabulary of the early writings on this particular aspect of dynamics is indicative both of the embryonic state of the art and also of the difficulties encountered by those wishing to learn or to communicate on the topic.

40. Illustrations in works such as

i) Ahrons, E.L., The British Steam Railway Locomotive 1825-1925, The Locomotive Publishing Company Ltd., London, 1927, and

ii) Alexander, E.P., Iron Horses 1829-1900 (a collection of contemporary lithographs and line drawings of American locomotives), Bonanza, New York, 1941

reveal that between about 1850 and 1865 the use of driving-wheel balance weights increased so that by the latter date the practice, for outside-cylinder engines, was general.

41. See, for example,

i) Correspondence on the subject in Engineering, 1894-5, volumes lvii, lviii, and lix.

ii) Kernot, W.C., 'On the Balancing of Locomotive Engines', Australasian Association for the Advancement of Science, Melbourne, 1901.

iii) Pettigrew, W.F., A Manual of Locomotive Engineering, Charles Griffin & Co., London, 1909, 3rd (revised) edition.

These sources indicate that as the nineteenth century drew to a close difficulties were being encountered because counterbalances of incorrect weight were being applied in the wrong position.

42. Duffy, M.C., Rail Stresses, Impact Loading and Steam Locomotive Design in the 19th and 20th Centuries, Stephenson Bicentenary Address, given at Sunderland Polytechnic, 9 June 1981, p.17.

43. The calculations, drawings and photographs of these locomotives are in the possession of the North Western Museum of Science and Industry, Manchester.

44. The correspondence was initiated by an article on the 'Stability of the Locomotive as a Carriage' by an unnamed author who merely identified himself by the

letter 'C', The Engineer, 15 February 1856, p.75. It continued over a period of several months, concluding on 6 June 1856.

45. The Engineer, 11 April 1856, pp.198-199, author 'C'.

46. Op.cit., 28 March 1856, pp.166-167, author 'C'.

47. Op.cit., 4 April 1856, p.187, author 'W'.

48. Op.cit., 14 March 1856, p.136, author 'KRU'.

49. Op.cit., 11 April 1856, p.198, author 'KRU'.

50. Op.cit., 30 January 1880, p.82.

51. Reed, Brian, 150 Years of British Steam Locomotives, David & Charles, Newton Abbott, 1975, p.26. Deals with the industrial environment in which the locomotive construction industry developed.

52. The Engineer, 18 April 1856, p.215, author 'A'. A comparative assessment of the running characteristics of French and British locomotives has not been attempted in this study but, in general, it seems that problems of unsteady motion do not characterise French railway engineering as they did in Britain. It is quite possible that the early theoretical work of Le Chatelier, confirmed by practical testing on two of the country's major railways, established good balancing practice on a far wider scale than occurred here. The organisation of the railway system in France, grouped into six major railways during the 1850s and always subject to government supervision, was conducive to closer control of locomotive design and operation, than was the case in Britain with its large number of small,

independent companies. Again, operating speeds in France were not so high as in this country and were, by law, subject to specified limits. The maximum speed permitted anywhere throughout the entire national rail network was 120 km hr^{-1} and this limit was maintained until 1937.

53. Engineering, 23 November 1866, p.392.

54. Kernot, W.C., op.cit., p.363.

55. Op.cit., pp.364-365.

56. For example, Klein's construction for finding the acceleration of a piston is given by Professor W.E. Dalby in the third edition of his book The Balancing of Engines, Edward Arnold, London, 1917, pp.172-174. However, in the fourth edition of this work this method is omitted in favour of a simpler alternative attributed to Mr G.T. Bennett, of Emmanuel College, Cambridge.

57. British Association for the Advancement of Science, 'First Report of the Committee...appointed to report on the Development of Graphic Methods in Mechanical Science', Newcastle-on-Tyne Meeting, 1899, pp.322-327.

58. i) Booker, P.J., 'Gaspard Monge (1746-1818) and his Effect on Engineering Drawing and Technical Education', Transactions of the Newcomen Society, Vol.34, pp.15-36.
ii) Booker, P.J., A History of Engineering Drawing, Chatto and Windus, London, 1963. Chapters 9 and 10 of this book are devoted to Monge and his work.

59. Singer, Charles, et al, A History of Technology, Vol.V, Oxford University Press, 1958, pp.492-493.

60. Hamilton, S.B., 'The Historical Development of Structural Theory', Proceedings of the Institution of Civil Engineers, Vol.1, Part III, 1952, pp.374-419.

61. Timoshenko, S.P., History of Strength of Materials, McGraw Hill, New York, 1953, Chapter VII.

62. Ferguson, Eugene S., Kinematics of Mechanisms from the Time of Watt, United States National Museum, Smithsonian Institution, Washington, 1962, Bulletin 288, Paper 27, pp.185-230.

63. Dalby, W.E., 'The Balancing of Locomotives, with Special Reference to Marine Work', Transactions of the Institution of Naval Architects, March 1899, pp.185-225.

64. Whereas steam engines could have large-bore cylinders, and in the case of stationary engines frequently did, the combustion characteristics in the spark-ignition engine restricted the size of the cylinder. Also whilst the double-acting steam engine gave two working strokes per revolution, the Otto-cycle engine produced only one working stroke in two crankshaft revolutions necessitating four times as many cylinders to obtain comparable torque characteristics. Thus, internal-combustion engines are of necessity, small-bore, multi-cylinder devices running at high-speed to produce their power and present a somewhat different problem from the point of view of balancing. Again, multi-cylinders give the opportunity for greater internal balance and this in combination with flexible

engine mounts provided an acceptable solution to the problem, although serious consideration of the topic did not occur until the second decade of the present century. In 1914 the following papers were read:

1. Fullagar, H.F., 'Balancing of Internal-Combustion Engines', Proceedings of the Institution of Mechanical Engineers, 1914, Parts 3 and 4, pp.559-580.

2. Lanchester, F.W., 'Engine Balancing', Proceedings of the Institution of Automobile Engineers, Vol.VIII, 1914, pp.195-278.

65. While in 1850 there were only two professional engineering Institutions, the Institution of Civil Engineers (founded 1818) and the Institution of Mechanical Engineers (founded 1847), between 1860 and 1897 professional technological interests were formalised by the establishment of ten separate Institutions or Societies and the early years of the present century witnessed a continuation of the process with the formation of separate Institutions of Automobile Engineers (1906), Structural Engineers (1908) and Locomotive Engineers (1911).

66. Dalby, W.E., op.cit., p.185.

67. Dalby, W.E., The Balancing of Engines, Edward Arnold, London, 1929, Fourth Edition, Preface, p.iii.

68. Dalby, W.E., 'The Balancing of Locomotives', Proceedings of the Institution of Mechanical Engineers, 1901, pp.1157-1208.

69. Op.cit., pp.1162-1163.

70. Reed, Brian, private correspondence, letter 29 July 1980.

71. Nock, O.S., private correspondence, letter 4 May 1982.

72. Dalby, W.E., The Balancing of Engines, Edward Arnold, London, 1902, First Edition.

73. Sharp, Archibald, The Balancing of Engines, Longmans, Green & Co., London, 1907.

74. Dalby, W.E., 'The Balancing of Locomotives', p.1163.

75. Op.cit., p.1197, comment by J. Fraser Masterton.

76. Duffy, Michael, 'Rail Stresses, Impact Loading and Steam Locomotive Design', History of Technology, Ninth Annual Volume, 1984, Ed. Norman Smith, Mansell, London, p.50.

77. Dalby, W.E., op.cit, p.1207. Professor Dalby's comment upon the communication of Mr S. Rendell.

78. This statement, which appeared in a letter to Engineering, 6 April 1894, p.458, without citation of the sources was subsequently repeated in a paper by Scoular, J., 'A method of balancing, revolving and reciprocating weights in locomotives, as applied to inside-cylinder engines', Proceedings of the Engineering Association of New South Wales, Vol.XVI, 11 April 1901, pp.64-79.

79. Track testing of locomotives, in the sense of determining performance capabilities goes back to the very early days of their existence. George Stephenson and Nicholas Wood constructed a device to measure draw-bar pull in 1818 whilst about 1837 a dynamometer car was built by Brunel, Babbage and Gooch. This type

of vehicle has been in continuous use ever since. There are, however, many and serious difficulties involved in carrying out tests whilst an engine is in normal service amongst the most important being changing gradients, curves, special restrictions, climatic and atmospheric variations plus the restrictions imposed by the necessity of making the test run conform to the arrangements of the normal traffic schedules. Certain features and components are extremely difficult or even impossible to observe when the engine is on the line.

80. Goss, William F.M., Locomotive Performance, John Wiley, New York, 1907, p.2. Remarkably, Goss stated that no member of the Purdue staff involved in establishing the test station had been trained in a railway motive-power department.

81. Chronologically, priority is due to Russia, where a testing station of restricted purpose was built in 1881-2. Although a test plant in the sense that it was used to investigate steam-jacketing and compounding it did not have the facility for accepting a locomotive under normal operating conditions. The locomotive was mounted clear of the track and its power output was absorbed, via a belt transmission from the drivers, in operating workshop machinery. The results of this work are described by Borodin, Alexander, 'Experiments on the Steam-jacketing and Compounding of Locomotives in Russia', Proceedings of the Institution of Mechanical Engineers, 1886, pp.297-354.

82. Carling, D.R., 'Locomotive Testing Stations', Transactions of the Newcomen Society, Vol.XLV, 1972-73, pp.105-182.

83. Goss, William F.M., op.cit.

84. The actual report of this series of experiments is given in Chapter XVIII (pp.321-332) of Goss's book - ref.80.

85. Goss, op.cit., p.8. This illustration shows the locomotive positioned on the friction-brakes, designed by Professor George I. Alden, which provided the load to the locomotive.

86. Op.cit., p.323, Fig.197.

87. Op.cit., p.325, Figs.200 and 201.

88. Op.cit., p.328.

89. Op.cit., pp.331-332.

90. Clark, D.K., Railway Locomotives: Their Progress, Mechanical Construction and Performance with the Recent Practice in England and America, Blackie & Son, Glasgow, 1860, p.170.

91. Dalby, W.E., 'The Balancing of Locomotives', Proceedings of the Institution of Mechanical Engineers, 1901, p.1174.

92. Op.cit., p.1176, Fig.11.

93. Op.cit., p.1179, Fig.12.

94. Op.cit., p.1177.

95. Op.cit., p.1182.

96. Op.cit., p.1184.

97. Report of the Bridge Stress Committee, Department of Scientific and Industrial Research, HMSO, London, 1928.

98. Clark, D.K., 'On the Improvement of Railway Locomotive Stock and the Reduction of the Working Expenses', Proceedings of the Institution of Civil Engineers, Vol.XVI, 1856-57, p.18.

99 Brewer, F.W., 'Historical Notes on the Counterbalancing of British Locomotives', The Locomotive, 15 December 1930, p.419.

100. Duffy, M.C., Rail Stresses, Impact Loading and Steam Locomotive Design in the 19th and 20th Centuries, Stephenson Bicentenary Address, given at Sunderland Polytechnic, 9 June 1981, p.2.

Chapter 4

SOME UNCONVENTIONAL LOCOMOTIVES

It has just been shown that the internal disturbing forces generated by the mechanism of the locomotive were partially balanced in the horizontal direction, and hence the nosing of the vehicle on the track was reduced, by the insertion of balance weights in the driving wheels. Although this expedient effected an improvement in the stability of the locomotive on the rails and diminished the variation in the draw-bar pull of the engine on its train these benefits were only achieved at the expense of introducing unbalanced forces acting on the upper surface of the rails. While this effect was acknowledged and noted by workers such as William Fernihough and D.K. Clark it was dismissed as being of no practical consequence. With the relatively slow speeds then in normal use the "hammer-blow" effect had not manifested itself as a separate issue. This was to emerge later in the nineteenth century when heavier locomotives were run at higher speeds. Thus, the whole exercise of securing an acceptable mode of behaviour of the engine on the track, inappropriately but nevertheless universally and persistently called 'balancing', had as its objective the attainment of an acceptable compromise between the nosing, pitching, rolling and surging tendencies of the moving vehicle.

The potential difficulties associated with a recriprocating mechanism were perceived during the 1830s, notably George Heaton's experience with his steam carriage and J. Bodmer's patent of 1834 mentioned earlier, long before the

publicity given to the unsteady running of locomotives by the work of the Gauge Commission, and designs were produced and patents were taken out to remedy the deficiencies of the conventional two-cylinder steam locomotive. It is the object of this chapter to examine some of these specifically unconventional locomotives. While a few of them came to fruition in the construction of actual locomotives and seemingly, on the scant and inconclusive evidence, almost as quickly disappeared into oblivion, many, indeed most, never progressed beyond the paper of the drawing sheet or of the patent specification.

Earlier comments, in Chapter 1, about the inadequacy of source materials available on the conventional and therefore longer enduring locomotives are even more pertinent to the type of engine now under consideration and this makes the problem of lack of evidence even more acute and the task of the historian more difficult. However, the lack of complete details cannot conceal the genuine concern of engineers to solve the problem of producing a more 'steadily running' locomotive and the available evidence, sparse and incomplete though it may be, provides us with an insight to the thoughts of the engineers concerned.

The designs envisaged or produced to overcome or obviate the inherent deficiencies of the conventional two-cylinder locomotive with cranks at right-angles may be conveniently grouped under five headings and will be considered as such here. The categories being

1. Single-cylinder locomotives.
2. Opposed-pistons working in a cylinder.
3. The use of reciprocating balance masses.
4. Multi-cylinder locomotives.
5. Designs avoiding the use of reciprocating steam engines.

1. Single-cylinder locomotives

In December 1862 a serious suggestion of a reversion to single-cylinder locomotives was put to the Institution of Civil Engineers by A.E. Makinson.[1] Acknowledging the high state of perfection to which the permanent way had been brought and the denunciation by eminent engineers of high speed on the railways as dangerous to the extent of even justifying, or demanding, Government interference for its prohibition, the author realistically acknowledged that the safe transit of passengers at high speeds was a problem to be solved rather than avoided. In the light of experience some of these engineers had obviously changed their minds. Whereas at the time of his evidence to the Gauge Commissioners G.P. Bidder was no opponent of high speeds by 1860-61 he declared to the Institution of Civil Engineers:

> ...he recollected the time when he thought an engine could scarcely be driven too fast; but now he would never again travel by express trains if he could possibly avoid it.[2]

Although generally against Government interference,

Bidder was of the opinion that the railway companies should be obliged to restrict speeds until the permanent way was strengthened.

Thus Bidder wanted stronger track while Makinson saw the solution in the design and construction of locomotives free from the internal disturbing forces which tended to make them leave the rails. The onus was on the locomotive engineer. Modestly, the author presented his paper with the hope that he could 'further the progress of engineering practice'. Essentially, his thesis was that the most serious of the disturbing forces were those causing 'sinuous motion' and since the origin of these was in the two cylinders with cranks at right-angles the defect was to be remedied by a return to the locomotive practice of sixty years earlier. With only Trevithick's engines in existence it is not really meaningful to speak of locomotive practice in the first decade of the century in a general way although it can be applied in connection with Makinson's view of the locomotive scene. As he told his audience, 'the early experimenters, Murdoch, Trevithick, and others, constructed their engines with a single cylinder only' and he regarded this as the optimum design. Subsequent deviation in the form of the introduction of a second cylinder, adopted as an expedient to facilitate starting and produce uniform motion, although adequate for the speeds then in use, was in fact a degeneration and inappropriate for the speeds being attained with more powerful locomotives in the second half of the century. His major purpose was to show that with respect to uniformity of motion the standard two-cylinder engine was surpassed in

performance by the single-cylinder locomotive at all speeds in excess of 26 miles per hour.[3]

The verification of this assertion formed the substance of his paper, which concerned itself with uniformity of motion rather than the 'dead centre' problem of a single cylinder engine. But even in this respect his thinking was deficient and his appeal to the ideal of Trevithick's early engines was inconsistent, for the Cornish mining engineer clearly recognised the superior motion to be obtained from a two-cylinder engine which he specifically stated, with reasons, in his patent specification of 1802.

> We also on some occasions produce a more equable rotary motion in the several parts of the revolution of any axis moved by steam engines, by causing the piston-rods of two cylinders to work on the said axis by cranks at one quarter turn asunder. By this means the strongest part of the action of one crank is made to assist the weakest or most unfavourable part of the action in the other, and it becomes unnecessary to load the work with a fly.[4]

Questioned about the difficulty of starting a single-cylinder engine, the author revealed that he had devised a means of overcoming this. It consisted of a pair of friction discs which were to be engaged with the two sides of the tyre of the driving wheel and operated, via a shaft carrying a worm-gear and meshing with teeth in the periphery of a friction disc, by a

handwheel from the driver's cab. His idea had already been patented earlier in the year.[5]

Discussion on the paper, which extended over two evenings, did not reveal a single contributor sympathetic to the proposal although it did provide evidence that one successful locomotive engineer had at least considered the matter and, in principle, had experimented with the design.

Robert Sinclair, at that time Locomotive Superintendent of the Eastern Counties Railway, and a man with much experience in locomotive operation reported that 'a long time ago' he had modified an engine, which had deteriorated in condition by long use as a ballast engine and which at a speed of 15 miles an hour was uncomfortable to ride on, by putting its two cylinders on the same centre. That is, from a dynamical aspect, he converted the machine into a single-cylinder locomotive. When it could be got to go he stated that it travelled at 60 or 70 miles an hour with 'perfect steadiness'.

'Perfect' is an adjective used liberally, indeed too liberally, by nineteenth century engineers and must be accepted with caution. In general, its use seems to imply that the person concerned was satisfied that a significant improvement over the existing state of affairs had been achieved rather than the ultimate condition upon which no further progress could be made or envisaged. Clearly this is so with respect to Sinclair's remarks since the use of wheels with conical tyres generated oscillatory motion in all railway vehicles, carriages as well as locomotives where this phenomenon was augmented by the inertia forces created and sustained by the engine

mechanism. By putting the two cylinders on the same centre he obviously eliminated the nosing tendency caused by the quadrature of the two cranks in the conventional design but this expedient did nothing to diminish the variation in the draw-bar pull and, whatever improvement had been accomplished, it is not unreasonable to conclude that the resulting motion of the locomotive was far from steady.

However, even if Sinclair's assessment is accepted at its face value it must be acknowledged that he frankly admitted that this desirable condition could not be achieved in general practice because of the difficulties of starting and reversing.

In favour of the single-cylinder engine, if it was equipped with a reliable and practical means of starting, it could be claimed that with a centrally positioned cylinder the tendency to nosing was minimised and it would be simpler in construction and contain fewer working parts than the two-cylinder locomotive. Preoccupation, seemingly to the point of obsession, with his scheme to avoid the nosing tendency of the two-cylinder locomotive, blinded Makinson to the greater dangers and defects of his own proposals. To have concentrated the whole power of a locomotive into one cylinder would have increased the variation in draw-ball pull and also have concentrated the thrust of the piston onto one point of the crank-axle, that is its centre and weakest region. This in itself was virtually justification for condemning the idea since the crank-axle was notoriously the most troublesome component in the inside-cylinder engine. However, such a mundane technical constraint might not deter the enthusiastic inventor and

certainly patents for single-cylinder locomotives were taken out in 1852[7] and 1856.[8] It is interesting to note in passing that whereas Britain succeeded in manufacturing sound double-throw crank-axles and inside-cylinder engines were common in this country during the second half of the nineteenth century, American experience was less fortunate with the result that this type of locomotive was a rarity across the Atlantic.

Certainly a single-cylinder would have restricted further progress in developing larger and more powerful engines because of both the limitation of space between the frames and the tendency of increasing the crank-throw to raise the height of the boiler. Indeed several of Makinson's critics complained that a result of his design was to raise the centre of gravity of the locomotive and the advocates of a low c.g. persisted for many years.

In seeking to explain the quite remarkable proposals of A.W. Makinson for such a late period it is possible to conjecture that his attention was drawn to the single-cylinder machine by the patent of Walter Neilson, referred to above, and more likely by the fact that locomotives to this design were actually built, by Neilson & Co., of Glasgow, for use on the colliery and ironworks railways of Scotland. Details of these engines were published in The Engineer[9] during December 1856, including drawings showing a side elevation, see Fig.4.1, and a sectional plan. The centrally positioned cylinder, 10 inches

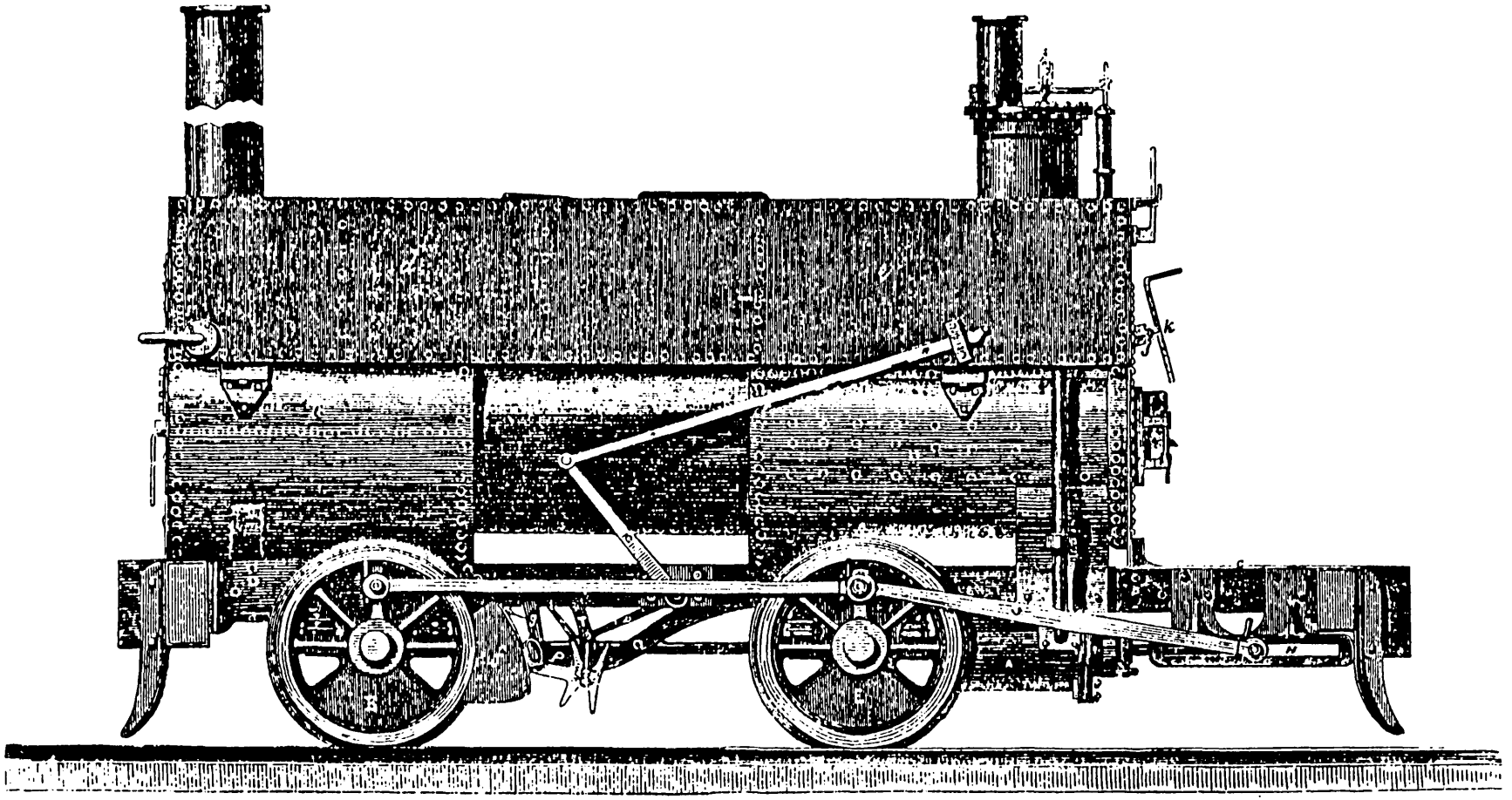


Fig.4.1 W. Neilson's single-cylinder locomotive

diameter by 16 inches stroke, was located beneath the firebox and the piston rod was connected to a crosshead beneath the footplate. The crosshead drove, via connecting rods on both sides of the locomotive, onto crank pins on the rear wheels which were coupled to the front wheels. To obtain a better action in passing the dead centres the crank pins on the two sides of the engine were in quadrature. What the difficulties were in starting these engines from a dead centre position we have no details although F.J. Bruton in his Newcomen paper[10] on industrial steam locomotives has suggested that it could have been a part of the duties of the fireman to move the engine with a crowbar or even physically pushing the machine; neither course of action could have been particularly easy especially as a frequent occurrence. It does not seem unreasonable to conclude that the art of driving the engine included the skill of bringing it to a halt with the piston in the region of mid-stroke. This might not always have been the end of the trouble, especially in frosty weather etc., because if the wheels were prone to slipping (although it must be remembered that it was a saddle tank engine) the engine would be most likely to stall on a dead centre position. Whatever the operating difficulties, they were presumably far from insurmountable because quite a number of these locomotives were built. Exactly how many is not known and this again highlights the difficulty of the historian. We have no contemporary record of their operational behaviour and we have no precise knowledge of the number built. Ahron's gives a few technical details[11] most likely culled from The Engineer but without further comment. According to Bruton about

a dozen[12] were built although this figure was challenged during the ensuing discussion and was amended to a number of about thirty.[13] Even if the lower figure is accepted this, in itself, is evidence suggesting that these machines gave satisfaction in service, although at slow speeds.

Aveling and Porter, of Rochester, an established builder of traction engines also introduced, in 1866, a single-cylinder industrial locomotive which, again according to Bruton, was fairly extensively employed. Essentially this was a traction engine on railway wheels and proved economical in service, operating at about only half the cost of using horses and, for equal work, consuming about half the amount of coal used by a conventional direct-coupled locomotive. The geared drive also gave a more uniform turning effort to the wheels which apparently did not require balance weights.

This firm built a single-cylinder locomotive as late as 1921 and according to G. Alliez, a contributor to the Newcomen discussion on Bruton's paper, an Aveling single-cylinder engine built in 1881 was still intermittently working in 1956.

However, the fact that these machines appeared in the late 1850s and, evidently, in some cases this type was still being used almost a century later, is no indication that it was capable of adaptation to high-speed passenger work. The haulage of coal, minerals, slate, and similar commodities in industrial regions or quarries was a far different proposition from the conveyance of passengers who, increasingly were becoming accustomed to expecting and demanding greater comfort in their travel. Undoubtedly the single-cylinder engine could have

diminished the nosing tendency of locomotives but apart from this the idea had nothing to contribute to locomotive practice in the 1860s nor its subsequent development.

2. Opposed-pistons working in a cylinder

2a. The designs of John George Bodmer

It was appreciated fairly early in the history of the steam locomotive that a true balance of reciprocating masses could best be achieved by the equal and opposite movement of other reciprocating masses, that is by the internal cancellation of inertia forces.

Credit for priority in recognising the importance of balancing the reciprocating parts of steam engines was claimed for John George Bodmer by H.T. Walker[14] in 1909 and this was repeated by E.L. Ahrons[15] some years later. Almost certainly, of course, Ahrons was dependent on Walker for his information about the Swiss-born engineer. Our only source of reference for details on Bodmer's locomotives is the series of short articles on the subject published in both The Locomotive[16] and also The Railway Gazette[17] during 1909. Arising from his interest in the origin of the four-crank balanced locomotive and failing to find information in periodical literature and text-books Walker was eventually led by the Gauge Commissioners' Report to Bodmer. As a result of his contact with Bodmer's family in Switzerland a large number of the engineer's working drawings of locomotives plus all his diaries and papers were made available to Walker and form the basis of his writing.

It must be emphasised here that the preservation of

Bodmer's drawings and papers is quite uncharacteristic of the fate of similar documents of many British engineers. Although his locomotive work was carried out in Britain and the associated drawings were produced here Walker located them in the safe custody of the engineer's family in Switzerland. Their survival is most likely attributable to the unique circumstances of Bodmer himself. Whereas British railway engineers worked for companies and the designs and drawings they produced were the property of and remained with the company, Bodmer during each of his three spells in this country operated on his own behalf. The diverse multiplicity of his designs, which included armaments, textile machinery, machine tools and a variety of devices besides his railway locomotives and stationary engines, and his several business enterprises obliged him, for his own reference and use, to carefully maintain and safeguard his own records. Presumably when he left London for Vienna in 1848 they went with him as was the case when he returned to his birthplace Zurich, in 1860, and on his death there four years later they passed to his family. Walker's articles are of especial value since they reproduce Bodmer's own drawings of his locomotive engines which in turn reveal his method of balancing.

Certainly Bodmer's patent of 1834 in which he made the claim for a balanced engine is the earliest record of the idea revealed by this study and seems to justify Walker's assertion. His scheme, as outlined in the specification was,

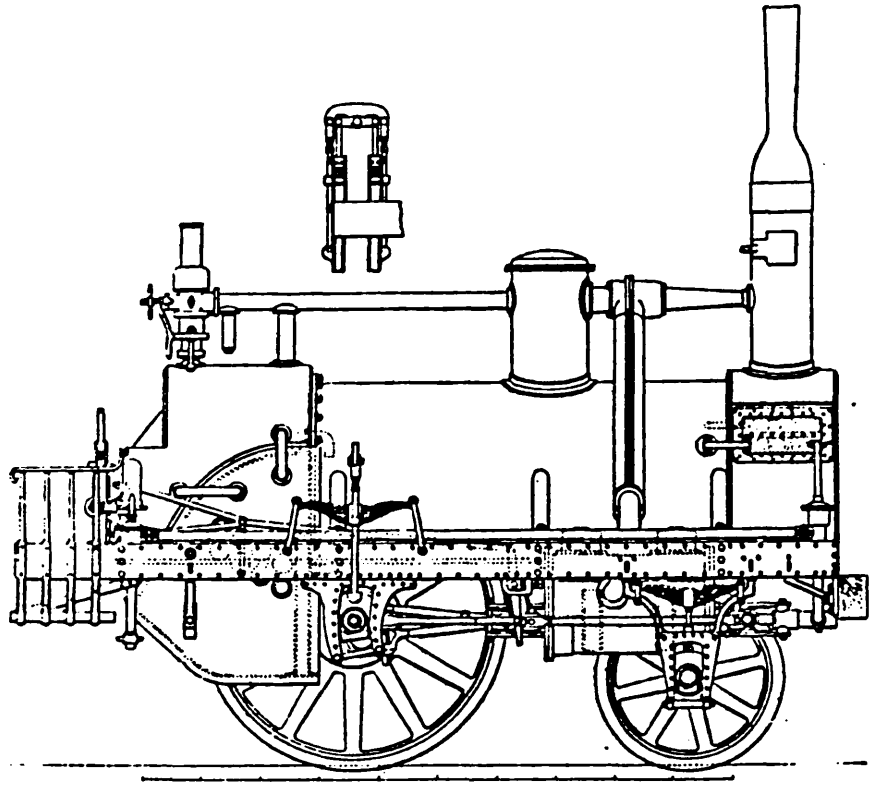


Fig.4.2 Bodmer's first locomotive.
Patent drawing of 1834

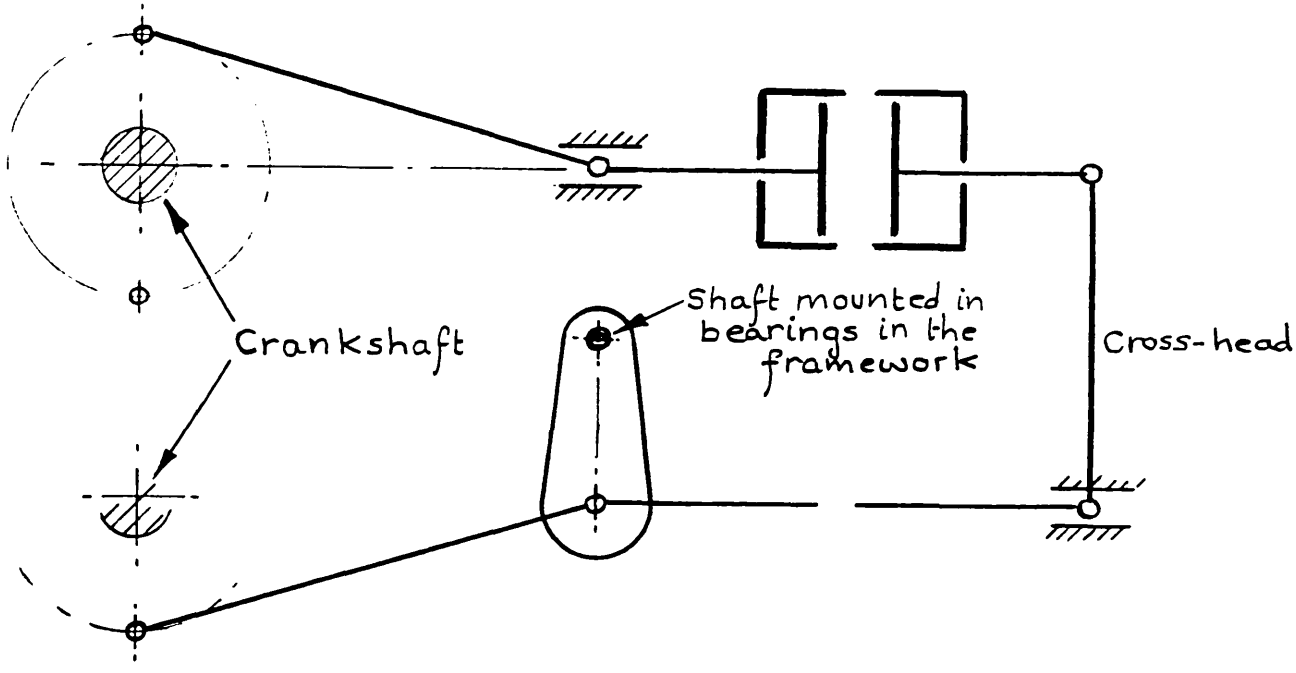


Fig.4.3 Schematic diagram showing the principle of operation of Bodmer's design for a balanced engine with a piston rod passing through each end of the cylinder

> ...The employment of two pistons in one cylinder, moving in opposite directions, each piston working a separate crank on the same shaft, by which arrangement the power applied to the shaft is balanced or equalized, for as one piston forces its crank one half of a revolution, the other piston pulls its crank the other half, thereby communicating a rotatory motion to the shaft without strain or stress upon its bearings; and further, that as the expansive force of the steam acts upon the pistons, and through them upon the cranks alone, it is evident that there will not be any strain exerted upon any part of the framework or foundation of the engines. By employing two pistons the power is doubled, and therefore, two cranks, each four inches radius, would exert the same power upon the shaft as one crank of eight inches, and the speed of the engine may be doubled without causing more wear and tear in the piston and cylinders than in engines of the ordinary construction when working at half the speed; and owing to the shortness of the stroke and increased size of steam ways, great speed can be obtained without diminishing the power of the engine.[18]

These patent claims were applicable to both stationary and locomotive engines but it is probable that the first balancing arrangement described in the patent specification and adopted for his first locomotive design, Fig.4.2, was never

used. On this inside-cylinder engine the two pistons had their rods extending through opposite ends of the cylinder, and each worked a separate crank on the same shaft. The principle of operation of this mechanism is shown in Fig.4.3. However, this, the first locomotive designed by Bodmer, was never built. An alternative design for the two opposed pistons working in one cylinder was also included in this patent and consisted of both pistons driving coaxially through the rear end of the cylinder. This was accomplished by the front piston possessing a solid piston rod which passed through the tubular piston rod of the rear piston, the piston rods being connected to separate crossheads. A diagrammatic representation of this is shown in Fig.4.4.

An experimental stationary engine, successful from a vibrational consideration was made in 1834 with a 10-inch diameter cylinder which, according to a later description,

> ...was simply bolted to posts in the middle of the workshop...and allowed to revolve at a speed of more than one hundred revolutions per minute, there was no perceptible shaking or vibration in any part of the building, which was a very old one.[19]

His very success, technically, militated against Bodmer's engine. The reciprocating parts being in balance could be and were made lighter than corresponding components in conventional steam engines and this development was not looked upon favourably by Peter Rothwell of Rothwell & Co.'s Union

Foundry, in Bolton, where Bodmer had hired a floor and built the engine. Two criteria were here opposed: technical excellence and economic performance. In the estimation of Rothwell the sophistication of a well-balanced engine was subordinate to the maximum use of iron and since a reduction in the weight of iron used per engine was not regarded as serving the profitability of the foundry the firm declined to manufacture the engines. The possibility of a superior engine selling in larger numbers and hence increasing business, if considered, was not seen as an opportunity to be exploited. Additionally textile manufacturers and others, like the railway engineers at a later date, were suspicious of the complexity of the mechanism, and cautious of the dangers of high speeds, besides the opposition of those who regarded him as 'a foreigner' and this, apparently, was not insignificant.

Evidence as to which of the two schemes of balancing was used in the earliest stationary engines is completely lacking and so whether dissatisfaction with the initial idea, possibly in the light of experience with an early stationary engine, or perhaps in response to charges of complication from his critics remains a matter of conjecture. However, when he designed his next locomotive, and the earliest drawing of this, Fig.4.5, is dated 31 May 1842, the opposed pistons were both driven from the rear end of the cylinder. And this arrangement, which was delineated in greater detail in his patent of 1843[20] was employed in the locomotives he subsequently built. By this time Bodmer was obviously convinced of its superiority over his

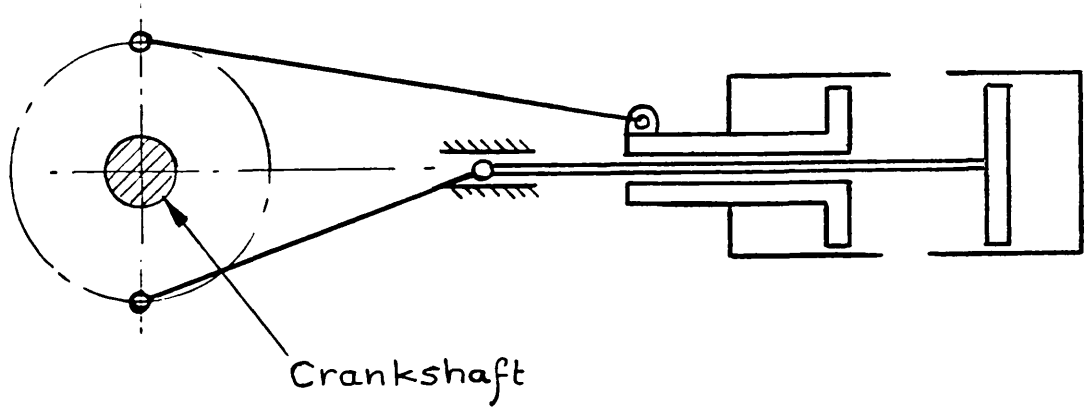


Fig.4.4 Bodmer's engine design using telescopic piston rods

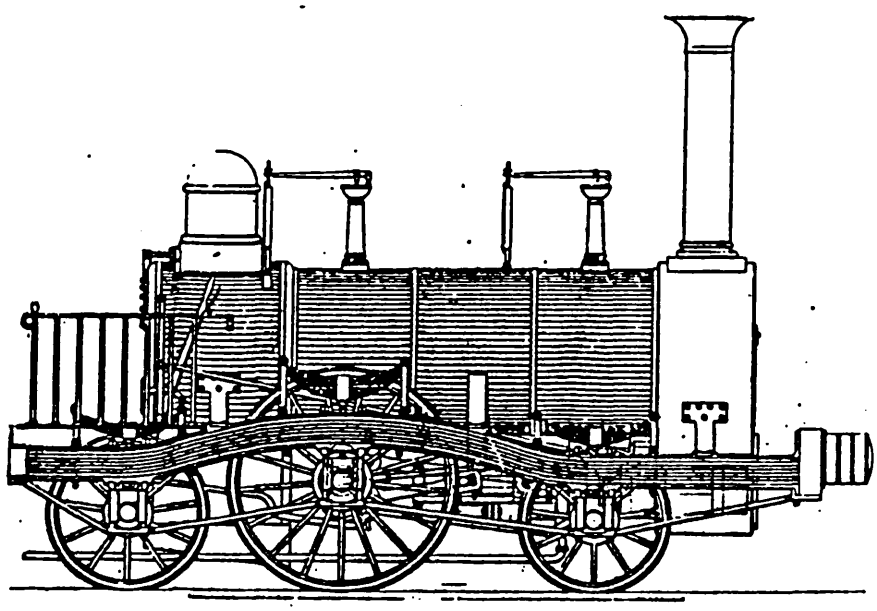


Fig.4.5 Bodmer's locomotive drawing of May 1842

original scheme and when, in 1845, he read his paper on Stationary and Marine Engines[21] to the Institution of Civil Engineers he was using this method exclusively.

Uncertainty prevails on the question of whether or not this engine was actually built. Bodmer's papers are characterised by many omissions and Walker's record is obviously incomplete but he does record that the drawings of this engine reveal that they had been sent into the shops and he further claimed that 'by patient investigation it had been learned that an engine very similar to it was built for the South Eastern Railway and designated by the builder (Bodmer himself) as No.1'.[22] Walker did not give details of the nature or methods of his enquiries and consequently it does not seem possible to evaluate his conclusion more closely although it appears to be corroborated by circumstantial evidence. Bodmer certainly told the Gauge Commissioners that he had been connected with locomotives for about three years and also that he had built three locomotives for the South Eastern Railway. His evidence before the Commission was given on 25 October 1845[23] which gives a close correspondence between the beginning of his association and the date of the drawing of his locomotive in question.

According to Walker, the diaries did not provide evidence that locomotive 'No.1' was sold to any railway and it is not unreasonable to conjecture that in order to convince the Directors of the South Eastern Railway of the power and reliability of such an unconventional and innovative design

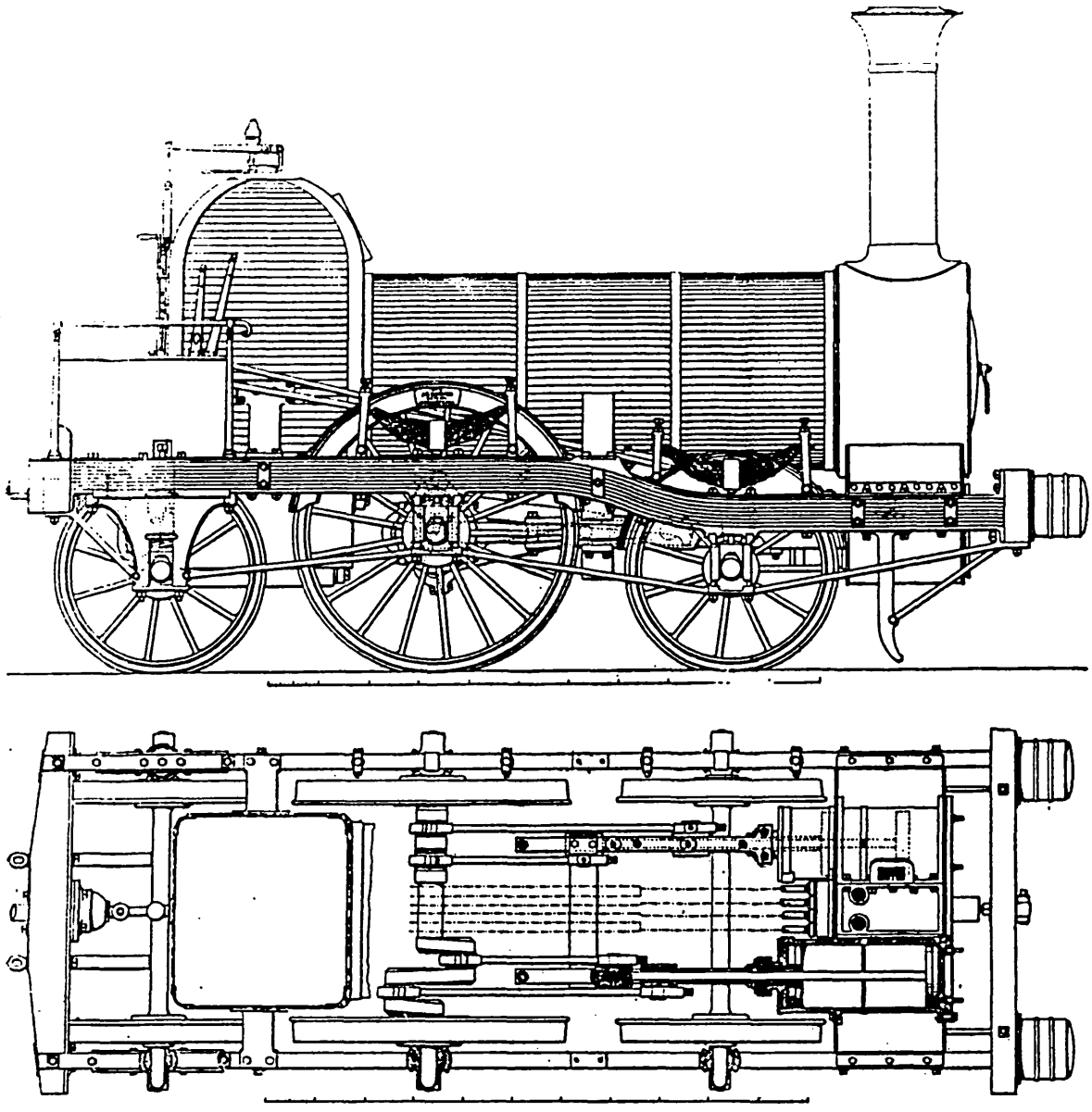


Fig.4.6 Bodmer's locomotive built for the South Eastern and Brighton Railway, 1845

Bodmer supplied the Company with an experimental prototype for a trial period.[24] The fate of the machine is unrecorded and it finally departed from view with a note in the diary, dated 11 October 1846, that his son, Rudulph, had informed him of its sale for £1,600. The purchaser was not mentioned.

If this surmise is correct, and Bodmer's own statement affirmed that he had constructed three locomotives for the South Eastern Railway, it is likely that the Company were suitably impressed by the engine for in July 1845 they took delivery of Locomotive No.2. (Fig.4.6). This inside cylinder engine had driving wheels 5ft 6in diameter. Each cylinder, 16 inches diameter, contained two opposed pistons each with a stroke of 15 inches, connected to cranks spaced 180 degrees apart, as shown in Fig.4.4. However, the double cranks associated with each cylinder were in quadrature. The general layout of the design may be seen in the plan view of Fig.4.6 which clearly shows the unequal length of the connecting rods used with the opposed pistons. The engine is of particular interest since it was the subject of some comment at the hearings of the Gauge Commission. A few witnesses, including Benjamin Cubitt[25] (locomotive engineer to the Brighton, Croydon and Dover Railways) commented upon its virtues, some of which contributed to its steady motion, but its opponents criticised the complexity of the machine.

Thus John Gray, the locomotive superintendent of the Brighton line, in admitting its steadiness of running observed 'The common engine well balanced arrives at the same thing with a great deal less parts'[26] and a similar opinion was shared and expressed by William Fernihough[27] of the Eastern Counties Railway. By the standard of the mid-nineteenth century conventional two-cylinder locomotive, complexity is a feature of Bodmer's engine that cannot be denied. The four-throw crankshaft, the four separate crossheads, the hollow and the

solid piston rods operating telescopically were all innovations and potential sources of trouble regarded with suspicion by contemporary engineers. Their combination in a vehicle generally acknowledged to be smooth-running, at a time when this was very much in the minds of engineers as an important characteristic of locomotive performance, was regarded as an unnecessary and an unacceptable refinement by these experienced engineers responsible for the day-to-day running of locomotives. In their view Bodmer's engine was a liability rather than an asset. Their judgement accorded it no superiority over the simpler, cheaper and more easily maintained conventional locomotive properly balanced. Clearly they were satisfied with the degree of stability achieved, or at least achievable, by the use of rim weights in the driving wheels.

Unfortunately for Bodmer at the end of August 1845 his locomotive was out of action undergoing repairs due to breakage of the front axle, an incident which occurred while it was hauling a passenger train. Adverse publicity, seemingly ill-informed, was not conducive to an objective appraisal of his engines. Their performance as powerful, smooth-running engines was testified by some of the country's leading practising locomotive engineers and there can be no doubt that in principle their design was sound. Constructed of better quality materials it is likely that their success would have been more widely acclaimed. However, at this early period in locomotive manufacture insistent demands for ever more constructional materials combined with deficient metallurgical knowledge, an absence of instrumentation (for example, pyrometers were not

introduced at Crewe until the beginning of the twentieth century) and no reliable methods - in our present sense - of material testing and quality control meant that inconsistencies in the properties of materials were an unknown hazard that had to be accepted and provided for in design. But in this, of course, they were not different from other contemporary railway engines. They, like virtually every other locomotive built in the early days, suffered from defects, inadequacies and mishaps but what was accepted as normal procedure with conventional engines was attributed to novelty in his designs. One of his engine failures, involving broken pistons, was caused by differential thermal expansion of the brass piston rings. Again, the tenders of these engines were faulty and accidents originating from this source were, apparently, blamed on the engines themselves. Probably, the fate of Bodmer's design was sealed by the fatal accident involving locomotive No.2 when on 23 May 1846, en route from Dover to London, it was derailed at a speed of about 40 mph, and killed the driver, an event which caused Bodmer much anguish. According to Walker, the attempt to attribute blame to the engine failed because of the evidence of J. Cudworth, the locomotive superintendent of the line, Major-General Pasley, and others. However, facts are not necessarily significant when minds are made up or prejudices are well entrenched. In 1849, a correspondent to the Railway Chronicle confidently apportioned blame for the accident to the novel design which was also the cause of the frequent repairs necessary to the locomotive.[28] It is, perhaps indicative of the lack of detailed knowledge at the time - and also of the

difficulty confronting the historian in attempting to assess the technical competence of the people involved - that the anonymous contributor responsible for this allegation, when challenged, shifted his ground to the extent of completely contradicting his original assertion and then, again without any substantiation, blaming the calamity on the permanent way.[29]

The locomotive was repaired and modifications, some the responsibility of Bodmer and others due to the railway company itself, were incorporated before the locomotive was put back on the line, where, apparently, it was used for experimental purposes before eventually being broken up in 1880. Whether the alterations included conversion to the conventional cylinder arrangement and drive is not recorded but the third locomotive supplied by Bodmer and Company to the Brighton Railway Company in December 1845 was rebuilt with ordinary cylinders in 1849. Despite the acknowledged merits of these machines as steady-running vehicles their relatively short life as supplied by Bodmer suggests that in the experience of the railway companies this desirable characteristic was certainly not paramount in their order of priorities. There was nothing unusual in making the occasion of a repair an opportunity to incorporate modifications but, nevertheless, the conversion of the third locomotive within four years - a very short period in the normal life of an engine, is an implicit acknowledgement that the opposed cylinder design possessed disadvantages which outweighed the advantages. Undoubtedly their complexity compared to the usual inside-cylinder locomotives would have made accessibility and the task of maintenance more difficult and costly, factors

hardly likely to commend the engines to the management and staff particularly so if they were not dissatisfied with the behaviour of their locomotives of standard design.

That Bodmer attached great importance to the matter of balancing engines is attested by his 1844 patent[30] for further improvements in locomotive, marine and stationary engines in which he claimed, but did not show, the invention of a four-cylinder balanced locomotive with a pair of inside cylinders working on a cranked axle, and the two outside cylinders working on crank pins, the two pistons of each pair of cylinders working in opposite directions. However, his attachment to the idea of opposed pistons working in one cylinder was strong, suggesting his conviction in the intrinsic worth of this arrangement, and manifested itself again in his design, produced early in 1846, for an outside cylinder balanced express locomotive, and to which he referred in his evidence to the Gauge Commissioners.[31] Once more the destiny of this design is, with our present state of knowledge, shrouded in mystery for, as Walker concluded his articles in The Locomotive,

> ...not a scrap of documentary evidence can be found to show that this engine was ever built, though the drawings show many indications of having been in the shops. They were beautifully executed, but they have been ruined by rough handling.[32]

An inherent weakness of Bodmer's design was the unequal length of the two connecting rods. The angularity of these

transmitted a vertical thrust through the cross-heads on to the guide bars and hence constituted a disturbing effect on the engine, this being more pronounced the shorter the length of the connecting rod. Different vertical thrusts were thus generated by the connecting rods of unequal length and this caused some problem for in his diary Bodmer recorded 'engine No.2 broke the short connecting rod'.[33] This difficulty was not peculiar to his design but rather was a matter to be considered with all conventional engines although, as noted earlier, the natural trend to longer connecting rods minimised these effects. Close though Bodmer may have come to the ideal of complete balance his design did not achieve it. Quite apart from the guide bar reactions, since the connecting rods for each cylinder were not coplanar, their inertia effects acting at different distances from the longitudinal axis of the locomotive generated a couple tending to turn the locomotive about a vertical central axis, alternately, in opposite directions. Furthermore, because the two rods, both in front of the driving axle, were always moving in opposite directions and the inertia forces on forward and return strokes were unequal true balance was unattainable. Thus the perception that the true balance of reciprocating masses required the equal and opposite movement of other masses was one thing, but its practical accomplishment quite another, because the mechanism required to produce the complementary motion itself introduced unbalanced forces. Such was the case with Bodmer's engine. The piston assemblies and crossheads were self-balanced but to secure this condition he required connecting rods in different planes which, as described above,

induced unwanted disturbing effects. Overall, then, he succeeded in reducing the magnitude of the resultant unbalanced forces within the locomotive but not in eliminating them entirely. He produced a better balanced engine but not a completely balanced machine.

As a result of his experience with the connecting rod failure he decided to equalise the lengths of the connecting rods although he did not give any details of how he intended to achieve this on his 'single-driver' engines and his method remains unknown. It was accomplished in his 2-4-0 goods tank locomotive, Fig.4.7, designed in 1844 by attaching the connecting rod associated with the solid piston rod to the coupling rod rather than, conventionally, directly to its crank.

A number of these locomotives were built in 1845-1846 for the Manchester and Sheffield Railway but the discrepancies between the two sources of information on them are significant and do not permit details to be established with any claim to accuracy. Thus, while Walker, basing his drawings on Bodmer's working drawings states that the cylinders were 17in diameter with a total piston stroke of 30in, and the driving wheels were 6ft 2in diameter.

G.A. Sekon[34] whom Walker cites as a source of information on these engines, gives the cylinder diameter as 18in and the stroke as 24in. Additionally he stated that these engines possessed driving wheels 4ft 6in diameter. It is possible, of course, that both sets of dimensions were quoted accurately and merely record variations deliberately introduced into the designs of the individual locomotives. Apart from the

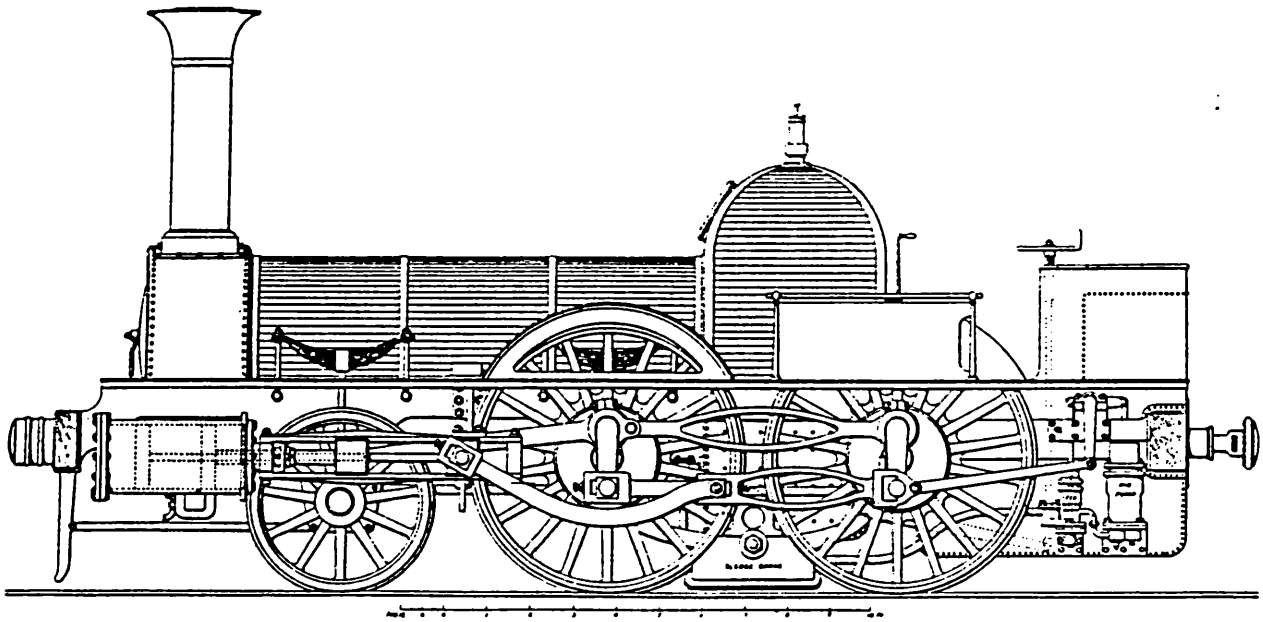


Fig.4.7 J.G. Bodmer's design of 2-4-0
Goods Tank Locomotive, 1844

fact that they were reputed to be powerful goods locomotives we do not have any record of the operational behaviour and life of these engines and once more, on the scant evidence, it is not possible to conclude other than whatever their merits, the design was not deemed worthy of repetition or development.

2b. J.G. Bodmer - concluding remarks

Bodmer was not a locomotive engineer, not even a railway engineer and his excursion into locomotive work was of relatively short duration beginning, according to his own statement to the Gauge Commissioners, about 1842. It lasted, perhaps, four or five years. Clearly he was outside the mainstream of British locomotive design and practice and, unlike many of his contemporaries, he had no railway operating experience. This must be regarded as an important deficiency because it is likely that a continuous, direct involvement with running locomotives would have led him to modify his designs as a result of comparing his machines with others of a more conventional kind. His locomotives have frequently been categorised by locomotive historians as 'freaks'. A trend which seems to have originated from the influential and authoritative pen of D.K. Clark, who in his book on railway engineering, while not illustrating Bodmer's engines or delineating his method of balancing nevertheless ackowledges its existence with the seemingly superficial and patronising dismissal, 'It is needless to add that Mr Bodmer's plan was too complicated for general use.'[35]

This of course proved to be the case. His opinion cannot be denied. But Clark was concerned with the contemporary state of locomotive technology and its economics. He did not attempt an evaluation of the potential of Bodmer's scheme to meet the balancing requirements of future locomotives or to compare it, in this respect, with the practice of putting rim weights in the driving wheels of engines.

If, however, hammer-blow problems had forced themselves to the attention of engineers earlier the situation would have been somewhat different and it is possible that his scheme might have been taken more seriously and have proved more influential. The fact that it possessed better characteristics in the vertical plane when engineers were not interested in these effects was an unappreciated virtue.

Following Clark, Clement E. Stretton was equally brief and condescending. In a single dogmatic and potentially misleading sentence he informed his readers that

> Mr Bodmer, in 1845, built an engine for the Brighton Railways, No.7, having his system of patent double pistons moving in opposite directions, but it proved a failure and was rebuilt.[36]

The unacceptable complexity of Clark's statement has now become failure, and of a number of reasons why the locomotive could be so classified none are given or even directly suggested. The implied hint, since its lack of success appears to be associated with the system of double pistons, is that it was attributable to technical inadequacy. This however, is the one aspect of the engine where contemporary evidence affirms its success.

Unquestionably one of the most inventive and versatile engineers of the nineteenth century, between 1834 and 1844 Bodmer took out 17 patents, he possessed the ability to perceive the true nature of a problem and find a technically correct solution. Nevertheless, history and the historian have not paid

much attention to John George Bodmer or accorded his work the recognition it surely deserves.

2c. Ritchie's Locomotive

The Engineer,[37] in its very first issue reported a new locomotive which had been seen in steam at Kew and which also was built with opposed pistons working in a single cylinder, Fig.4.8. The design of this engine, attributed to Mr Charles Ritchie, not only aimed to produce a properly balanced machine but also to solve a number of other problems confronting the engineer.

Like Bodmer's later designs the cylinders were outside, with the cranks on either side of the engine disposed at 90° to each other. To facilitate access to the cylinder covers and pistons the conventional cross-heads and guide bars were dispensed with in favour of a parallel motion mechanism in which the whole assembly of pistons and motion parts constituted a symmetrical arrangement in which corresponding components moved in opposite directions and produced a complete balance and hence freedom from the troublesome disturbing forces. However, the wheels were not coupled by the customary rods but by this flimsy-looking linkage which almost certainly, in the event of uneven tyre wear, was not robust enough to maintain synchronous motion of the wheels.

The outside-cylinder design avoided the weak and potentially dangerous crank-axle and to provide for safety should an axle fail the wheels were partially encased in guards strong enough to sustain the weight of the locomotive.

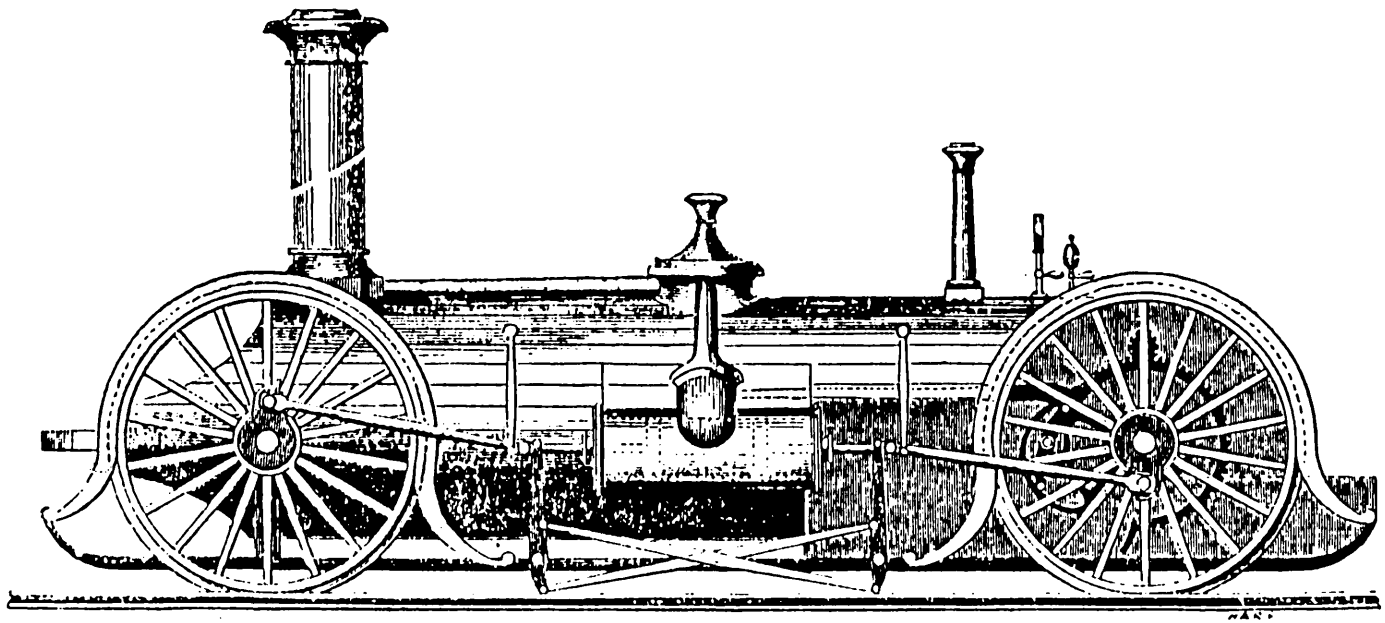


Fig.4.8 Ritchie's New Locomotive Engine, 1856

Furthermore, these box-section guards were lined with timber, elder being a suggested type, leaving just enough clearance to allow for the play of the springs, so that on the occurrence of a failure they acted as brakes. As the drawing reveals the designer adhered to the belief that the centre of gravity should be kept low and accordingly positioned the boiler very low between the axles which were placed at the extremities of the vehicle to keep the weight of the locomotive between the points of support.

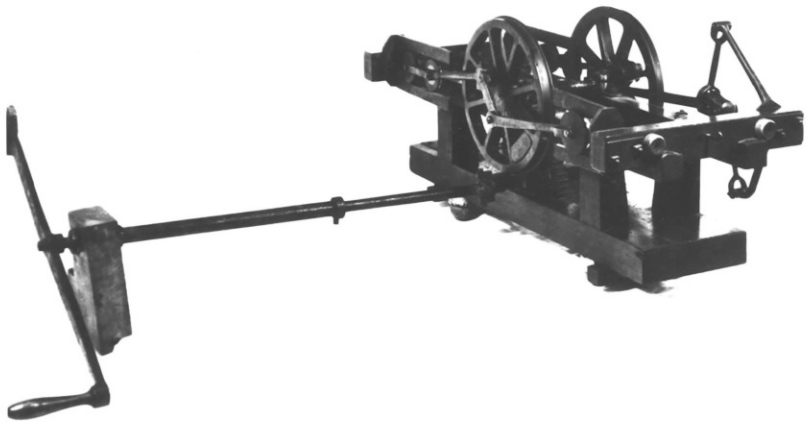
Use of the boiler as the main structural member of the whole engine was a reversion to Trevithick's practice at the beginning of the century and not a feature conducive to successful operation. And presumably the engine was not successful because its disappearance from the scene was as swift and complete as its appearance was sudden and unexpected.

When opposed pistons next appeared on a steam locomotive they were in separate adjacent cylinders and they will be referred to in section 4 of this chapter.

3. The use of reciprocating balance masses

Theoretical balance of a reciprocating mass would be achieved by a mechanism in which the mass to be balanced was connected to another reciprocating mass in such a way that their directions of motion were always opposed and this was secured by a symmetrical arrangement with a dummy crank and connecting-rod of such length that its obliquity was always the same as that of the connecting-rod driven by the piston.

This was George Heaton's solution[38] to the problem and



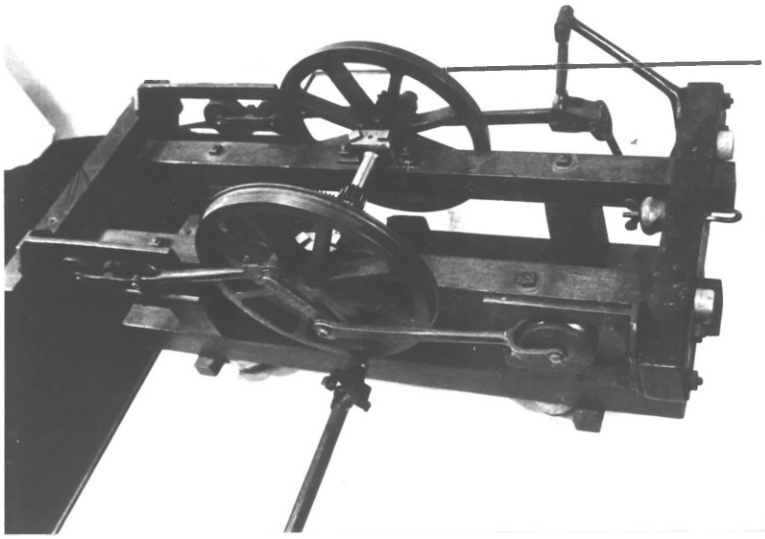


Fig.4.9 George Heaton's model

he made a model, Fig.4.9, to illustrate his ideas on the cause and prevention of oscillation in railway engines and this still exists, being in the possession of the Museum of Science and Industry at Birmingham.

Made to a scale of one-eighth, the model represents a locomotive with driving wheels 6ft diameter and cylinders 16 inches diameter with a piston stroke of 22 inches.

By means of an operating handle and gear train the pistons can be driven at the speed of those of locomotives at high velocities. If each wheel is balanced for revolving masses only, that is, it carries a balance weight in it equal to the weight of the crank pin and the boss which carries the crank pin, and the handle is turned slowly (without the auxiliary cranks) the machine remains stationary but as the speed is increased, it causes the model to oscillate and jump about. Since Heaton's object was to show the importance of moving weights in opposite directions to each other, a dummy piston together with connecting rod and crank, equal in weight to the piston and its mechanism, can be added to the model and their effect of producing steadier motion demonstrated.

In June 1848, McConnell[39] claimed that he had successfully experimented with the system at Wolverton but his statement is ambiguous and it is uncertain whether he adopted the method, or for how long it was used if he did. There is no evidence to indicate that it was employed to any significant extent on the London and North Western Railway or that it was even tried by any other company.

Despite the improvement in steadiness of the engine, the

design involved an extra connecting-rod, heavy cross-head and slide bars increasing the frictional resistance in the mechanism and thereby diminishing the tractive power of the locomotive. Together with the additional cost and complexity of the arrangement this was probably regarded as a greater disadvantage than the unsteady motion it sought to prevent.

Based upon a rational assessment of the balancing problem this design had little to commend it and, indeed, as Osborne Reynolds observed during 1882, in his series of articles 'On the Fundamental Limits to Speed',[40] it was rarely, if ever, adopted in practice. The idea is but another example of preoccupation with one aspect of the locomotive's behaviour obscuring other equally important matters. Makinson's advocacy of a return to single-cylinder engines to eliminate the nosing tendency has already been cited earlier in this chapter. Whereas Bodmer's opposed-pistons design, while effecting good balance also contributed to the power output of the engine, although at a cost of increased mechanical complexity, Heaton's arrangement, while also complicating the mechanism, actually absorbed power. This, in itself, was an unacceptable feature in the light of contemporary dislike of complexity coupled with the general and irreversible demand for more powerful locomotives.

Nevertheless, it is interesting to contemplate that in its day the scheme earned the approbation of the Society of Arts even if, many years later, it also received the undeserved opprobrium of G.A. Sekon, the locomotive historian.

Reference has already been made in Chapter 2 to the mounting concern over the unsteady motion of locomotives which

made it a major topic of discussion in the investigations of the Gauge Commission and led to the Society of Arts offering a Gold Medal for the best paper on the subject during the three consecutive years 1848, 1849 and 1850.

The Minutes of the Society[41] for these years make some scattered references to the matter, including a brief record of the receipt of a few communications from entrants both named and anonymous. In one or two instances a decision is simply minuted, 'resolved paper is not of sufficient merit to qualify for an award' and another more detailed note rejected the submission of 'F.B.R.' on the basis that it did not contain 'enough of novelty or of utility'. Apart from providing the historian with some evidence that a number of entries were received by the Society the absence of any detail on the nature of their ideas and proposals seriously diminishes the value of these books. Furthermore, even allowing for the illegibility, the documents are clearly not a complete and comprehensive record of the entries received nor the decisions made. Thus, while they do not contain any evidence, in the form of a note recording the fact, of an entry made by or on behalf of George Heaton they do signify the occurrence of such a submission.

The Minutes of the Committee of Mechanics for 14 July 1850 report the receipt of a letter, dated 14 February 1850, from the Secretary's Office of the London and South Western Railway. This letter, signed by Wyndham Harding, referred to the <u>return</u> of Heaton's paper, on the Causes of oscillation in Locomotive Engines, together with a 'model' and makes the observation,

> I consider the communication as sound and valuable, and as describing an enquiry conducted to useful results in a diligent spirit and in a mechanic-like manner. I think it worthy of a high class of medal and worth recording in our Transactions if room can be found for it.[42]

The minute book records that both Heaton's paper and Mr Harding's letter were read and that it was resolved that by his work and model, etc. Heaton was entitled to the Society's Gold Medal.

On the basis of this evidence it seems reasonable to conclude that Heaton's paper and model were submitted to Harding for assessment on behalf of the Society of Arts. Furthermore, the paper was most likely substantially the same as that he read to the British Association, at its meeting in Birmingham during 1850 while the model was that referred to above, now in the Museum in Birmingham. However, it is important to acknowledge that there is no proof of this.

The award of a Gold Medal appears to have been a reward for ingenuity rather than recognition of a practical solution to the balancing problem. Despite McConnell's undocumented assertions of successful trials the method was not adopted and this piece of research has not revealed further similar experiments until the appearance of the 'Krauss' locomotive in 1901. Further reference to this engine will be made later in this section.

From Harding's letter, quoted above, it is clear that he

was also impressed by the skilled craftsmanship exhibited in Heaton's model and another factor, i.e. personal acquaintance with George Heaton, possibly influenced his judgement on the matter. During the 1830s Harding was a pupil of T.L. Gooch, one of the Assistant Engineers under Robert Stephenson with responsibility for the northern end of the London and Birmingham Railway. Later, at the time of the Gauge Commission, Harding worked for this railway. Obviously, he was in the Birmingham area at the period of Heaton's intense activity in the field of balancing and it is not unreasonable to assume that he was acquainted with both George Heaton and his work. However, neither the honour bestowed on the man nor the recognition accorded his design gave it any practical advantage in locomotive performance and in this field of engineering it was not exploited although it is necessary to acknowledge, as mentioned in Chapter 3, that the method of using bob weights for engine balancing was successfully adopted in marine engineering.

Impracticable though the idea may have been for adaptation to railway locomotives it was sound as an exercise in theoretical mechanics and, as the work of A.F. Yarrow[43] had shown, it could be profitably employed in some circumstances.

3a. The Patent of A.W. Makinson and W.F. Batho

At the beginning of 1862, the year in which he read his paper 'On some of the Internal Disturbing Forces of Locomotive Engines' to the Institution of Civil Engineers, A.W. Makinson

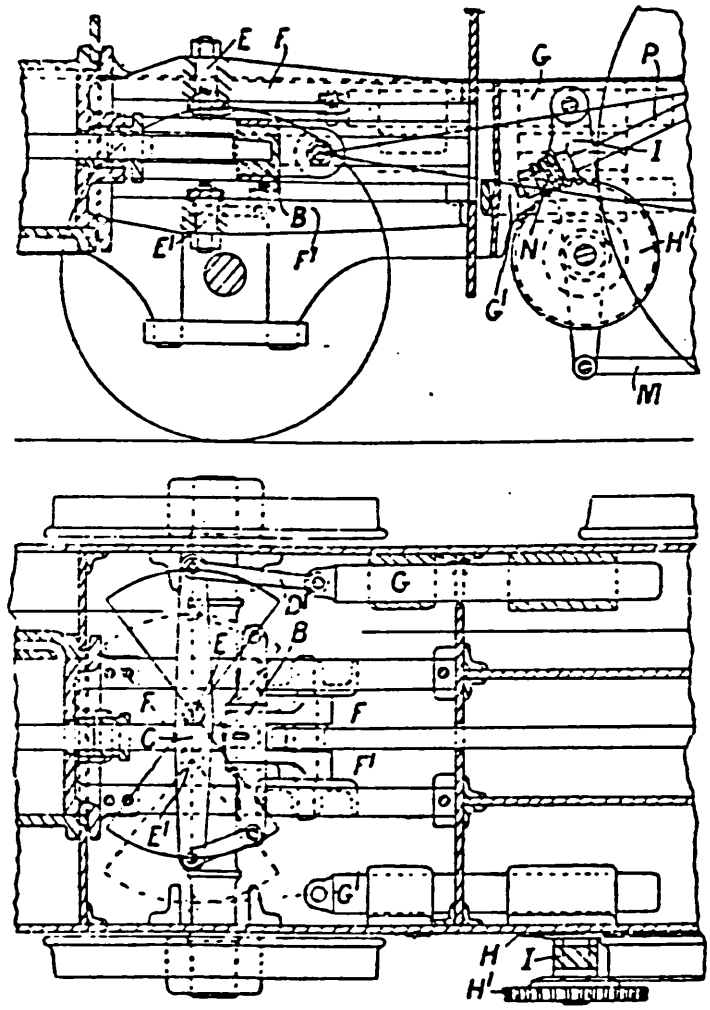


Fig.4.10 The design of A.W. Makinson and W.F. Batho for balancing a single-cylinder locomotive with reciprocating balance masses

together with W.F. Batho, took out a patent[44] for a design to balance the reciprocating parts of the single-cylinder locomotive by means of reciprocating balance masses. Their scheme is illustrated in Fig.4.10.[45] It consists of a system of levers, actuated by the crosshead, which drove two balance masses (one on either side of the engine) in a reciprocating motion equal and opposite in direction to that of the crosshead.

Once again, we find concentration upon solving one problem leading to the introduction of a complex arrangement of levers, pin joints and heavy balance weights to be driven in guides significantly increasing frictional losses and hence the power required to operate the mechanism itself. And this, of course, with a cylinder of limited size and restricted maximum steam pressures, could only be at the expense of the power which otherwise would have been available for traction. Only the total failure of the customary rim balance weights to give adequate counter-balance and hence an acceptable mode of locomotive vehicular behaviour would have induced the engineers involved to have adopted such mechanical complication with the inherent loss of haulage capacity. This extremity was never reached and consequently the use of reciprocating balance weights was never either seriously contemplated or adopted in general locomotive practice.

3b. The Krauss Locomotive

The prominence of engine balancing in the deliberations of marine engineers during the latter years of the nineteenth century has been briefly noted in the preceding chapter. Whilst,

generally, in terms of actual practice, this had little effect on locomotive engineers in one or two isolated cases possibilities for exploitation were perceived.

Herr Otto Schlick certainly regarded his method of balancing multiple cylinder engines as applicable to locomotives and protected it by patent in 1894.[46]

In 1900, the German company, Locomotivfabrik Krauss, displayed in the Paris Exhibition a quite remarkable express locomotive and one in which the basic design philosophy was not to eschew complication and sophistication. It is illustrated in Fig.4.11.

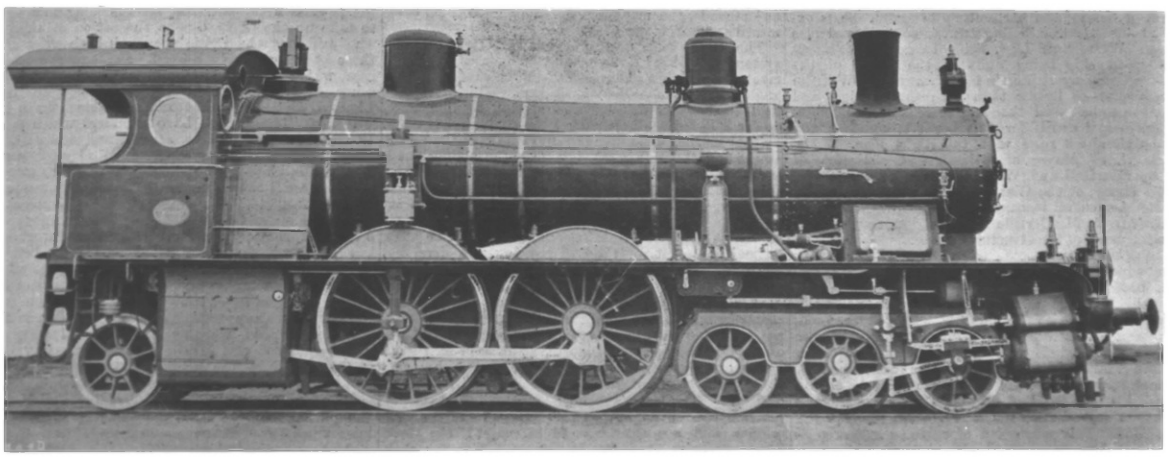


Fig.4.11 The Krauss Locomotive

As Engineering rightly observed,

> The most striking feature of the engine is the auxiliary axle placed between the forward pair of truck axles, and on which is placed a pair of wheels, usually raised clear of the rail. By means of a system of control gear, these wheels can be lowered to the rail and converted into an extra pair of driving wheels when the necessity of the service requires.[47]

These auxiliary wheels, driven by two high-pressure cylinders, outside the frames, were for starting heavy trains and to assist in negotiating steep inclines. They were not used for speeds in excess of 40 mph.

For express running the locomotive was powered by its inside compound cylinders. The high-pressure cylinder had a diameter of 440mm and the low-pressure cylinder a diameter of 650mm. The unsymmetrical displacement of the longitudinal axes of these cylinders about the axis of the locomotive obviously warranted serious consideration of the balancing of the moving parts. In the response we find the direct influence of marine practice and the only documented evidence that this study has revealed of bob weights being used by a prominent locomotive constructor. Cast-iron blocks, located in guides mounted between the coupled and rear axles, were driven by connecting-rods. Fig.4.12 shows the arrangement.

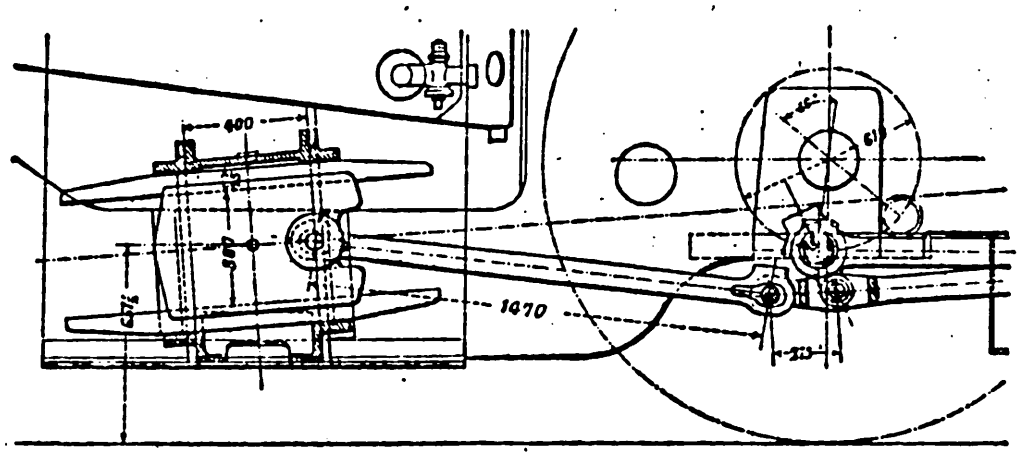


Fig.4.12 Reciprocating balance mass on the Krauss Locomotive

Unfortunately, it has not been possible to determine the effectiveness of Yarrow's system of balancing incorporated in this engine. Inextricably combined with other innovative features of the design it did not, apparently elicit separate and special comment at the time and like many other unconventional engines the fate of this machine if not unrecorded is certainly obscure. Lack of time and facility has prevented this particular matter being pursued further but it does not seem unreasonable to conclude that, so far as balancing is concerned, the locomotive was not influential.

3c. French 2-8-2 Tank Engines

Although not typical of general practice either in France or elsewhere the balancing of the two cylinder side-tank engine built in the 1930s for suburban service on the Northern Railway of France illustrates good balance secured by the ingenious exploitation of an opportunity presented by other design parameters.[48,49]

These engines were fitted with Cossart Rotary valve gear which was actuated by rods and levers through motion derived from a return-crank on either main crank-pin. This layout is shown in the following diagram, Fig.4.13.

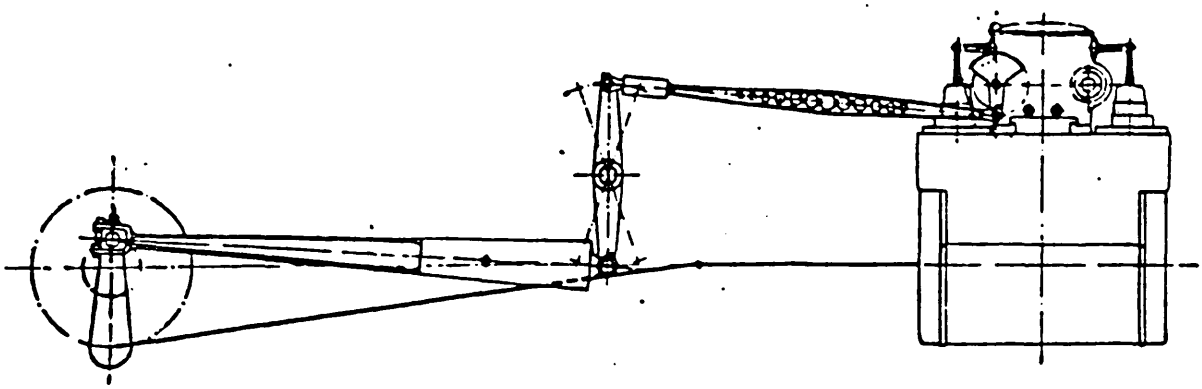


Fig.4.13 Balancing arrangement on French 2-8-2 Tank Engine

As will be seen from this, the rod between the crank-pin and the suspension lever has a reciprocating motion which is opposed to that of the piston connecting-rod, the piston and its

accessories. By loading the former rod with a balance mass the reciprocating masses could be balanced to any desired amount. On these particular locomotives a mass of 500kg was used to balance 40 per cent of the reciprocating masses, no part of which was balanced in the wheels.[50] The success of this arrangement was reported by The Locomotive by comparing it with the four-cylinder machine,

> In this two-cylinder engine M. Cossart has retained much of the balancing effect without mechanical complication or added cost of upkeep, and even at the high velocity of 7 turns per second nothing adverse to this device has come to light.[51]

Although not applicable as a general balancing technique and therefore something of an exceptional and isolated case made possible by the use of this particular form of valve gear it does, nevertheless, provide more evidence of the great attention being given to the subject in the years following the publication of the Report of the Bridge Stress Committee. A trend which was materially assisted by the conscious attempt to reduce the weight of motion parts by the adoption of alloy steels and a reduction of cross-sectional dimensions.

3d. Contra-rotating balance weights

It is, perhaps, surprising that among the many unusual, sometimes more accurately described as bizarre, designs produced for locomotives during the nineteenth century - some of them

specifically aimed at solving the problem of balancing the inertia forces of reciprocating masses - the artifice of employing contra-rotating balance weights does not even seem to have been suggested.

The impracticality of the idea could be advanced as an explanation for this apparent failure of the scheme to surface on the paper of engineers and inventors, both amateur and professional. But all of the evidence surviving from this period, some of it considered earlier in this chapter, does not indicate that feasibility was a significant criterion. Nor did it deter the presentation of quite eccentric ideas.

M. Tolle, in his consideration of locomotive balancing, acknowledged the possibility and showed that two contra-rotating shafts or gears carrying equal balance masses could completely balance a reciprocating mass.[52] His diagrammatic explanation of the method is shown in Fig.4.14.[53]

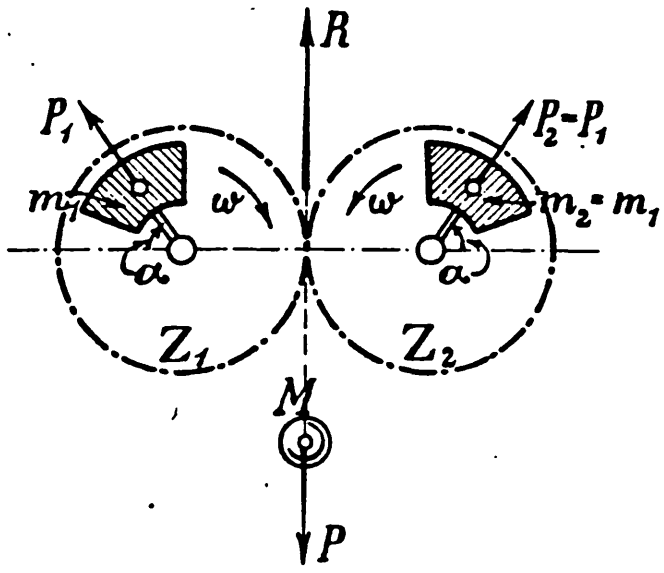


Fig.4.14 M. Tolle's scheme for balancing by the use of contra-rotating balance masses

This refinement of W. Fernihough's use of one revolving mass to balance a reciprocating system avoids the introduction of an unbalanced component force at right angles to the line of stroke. By equally dividing the single balance mass and positioning the halves on shafts turning in opposite directions, the component forces of these two equal masses in the line of stroke balance the inertia force of the reciprocating system while their component forces at right-angles to the line of stroke neutralise each other. But this elegant, seemingly simple, and theoretically superior method of balancing never made any contribution to overcoming the dynamic problems of locomotive performance. Its eventual development and use was within the field of internal combustion engines.

Fernihough's method was simple, the single balance mass was easily positioned in the driving wheels of an engine. Such facility was not inherent in the arrangement under discussion. The contra-rotating masses had to be co-planar and in turn their plane of rotation had to coincide with the axis of the reciprocating masses. This requirement was not easily met with the large masses involved in locomotive engines and it is not surprising, therefore, that the technique did not find application in this field. Tolle, himself, having outlined the difficulties concluded that general opinion accepted partial balancing as adequate.

4. Multi-cylinder locomotives

The use of more than two cylinders whereby the motion of one set of reciprocating parts could be counterbalanced, either

wholly or partially, by another set was a far more rational approach to securing dynamic equilibrium and it is not surprising that a few ideas and experiments on this theme emerged during the nineteenth century. Such designs obviously had the potential for contributing to the power output of the locomotive.

The early appearance of this idea, with Bodmer's patent of 1834 and his subsequent locomotive designs and locomotives, has already been considered in Section 2 of this chapter. With two cylinders, each containing two opposed pistons, he was effectively seeking the advantages of a four-cylinder engine but with only two cylinders to manufacture and maintain. Quite possibly the technical and economic advantages of such an arrangement seemed significant in the light of contemporary production technology. In the mid-1830s, when his patent was taken out the requirement of only two bored cylinders per locomotive instead of three or four must have appeared as a sound engineering decision. The task of fitting two pistons to one cylinder was quite possibly considered preferable to matching two pistons to two cylinders. However, it must be acknowledged that Walker's study of Bodmer's locomotives, based on the engineer's diaries and notes, does not reveal that the reason was ever explicitly recorded. Ten years later, in his patent for improvements in engines, he claimed - as mentioned earlier - the invention of a four-cylinder locomotive.

It was during the late 1840s, with the construction of two three-cylinder locomotives to Stephenson and Howe's patent[54] of 1846 that the first serious attempt was made to introduce

multi-cylinder locomotives into railway operation. Before considering this, mention must be made of a three-cylinder locomotive patented in 1839, thus having the priority for such a design.

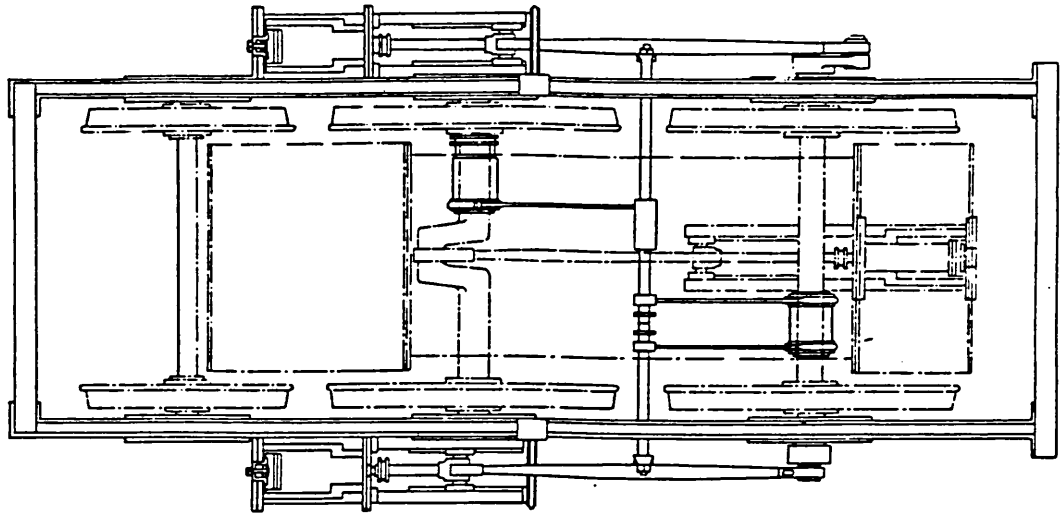
4a. The Three-Cylinder Locomotive of Isaac Dodds and William Owen

Isaac Dodds, a former pupil of George Stephenson, devoted himself in the years 1838-1845 to the improvement and manufacture of railway equipment.[55] In 1839 he became associated with William Owen, an inventive engineer with an established reputation for the production of forgings (before the invention of the steam hammer), and in this year they jointly took out a patent[56] for improvements to locomotive engines.

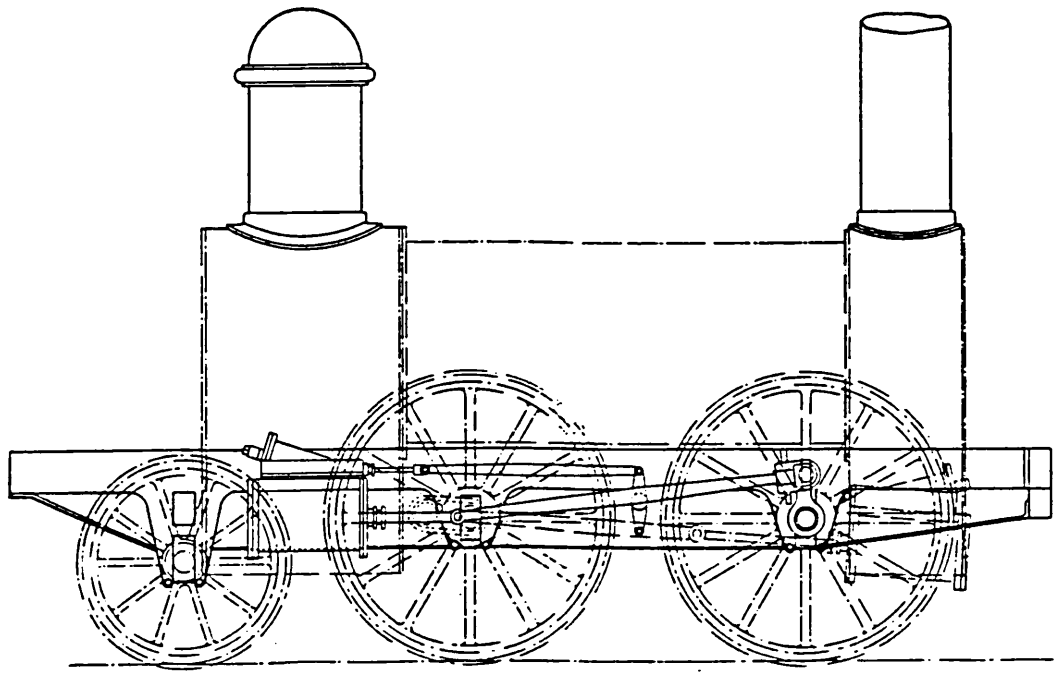
Amongst the improvements was the elimination of coupling rods between the driving wheels,

> ...by applying the power of two or more engines direct to two or more different shafts or axles of the wheels, thereby making all these wheels driving wheels.

To achieve this they claimed that two or more cylinders could be used although they expressed their preference for three cylinders and their patent specification drawing showed a three-cylinder locomotive. This is reproduced as Fig.4.15.



THREE CYLINDER LOCOMOTIVE (PLAN)



THREE CYLINDER LOCOMOTIVE (ELEVATION)

Fig.4.15 The three-cylinder locomotive of I. Dodds and W. Owen

As may be seen from this the engine had two outside cylinders at the rear of the locomotive, located at the side of the firebox and a central, inside cylinder positioned beneath the smokebox. In this 0-4-2 engine the outside cylinders were to drive the front wheels while the inside cylinder powered the rear driving axle. The specification made provision for an alternative cylinder arrangement in which all three cylinders were to be placed in line, in the smokebox. This proposal was not without a major drawback. It would have resulted in a very short connecting rod for the drive on to the front axle.

While this design is of some interest in that it shows that these engineers were thinking in terms of a layout which offered the potential for securing a better-balanced machine it cannot be claimed that the intention was to improve the steadiness in any way. The drawing of the locomotive shows cylinders all of equal size and does not indicate a conscious attempt to achieve an optimum degree of balance. Indeed, at the time of the patent the issue of balancing locomotives had hardly acquired the prominence it was destined to achieve within a few years. According to Snell[57] both the Dodds, father and son, were in the habit of conducting costly experiments with a variety of mechanical devices but there is not any known evidence, at present, to suggest that the three-cylinder locomotive project ever materialised. It is possible, however, that the idea sowed the seed which germinated and subsequently came to fruition in the patent and the locomotive of Stephenson and Howe.

4b. The Balanced Locomotives of Stephenson and Howe

The three-cylinder design patented by George Stephenson and William Howe in 1846 was specifically aimed at minimising the rolling action of the locomotive caused by the difference in slide bar reactions on each side of an outside cylinder engine with its cranks set at 90 degrees. Fig.4.16 showing this locomotive is reproduced from J. Warren's history of locomotive construction by Robert Stephenson & Co.[58]

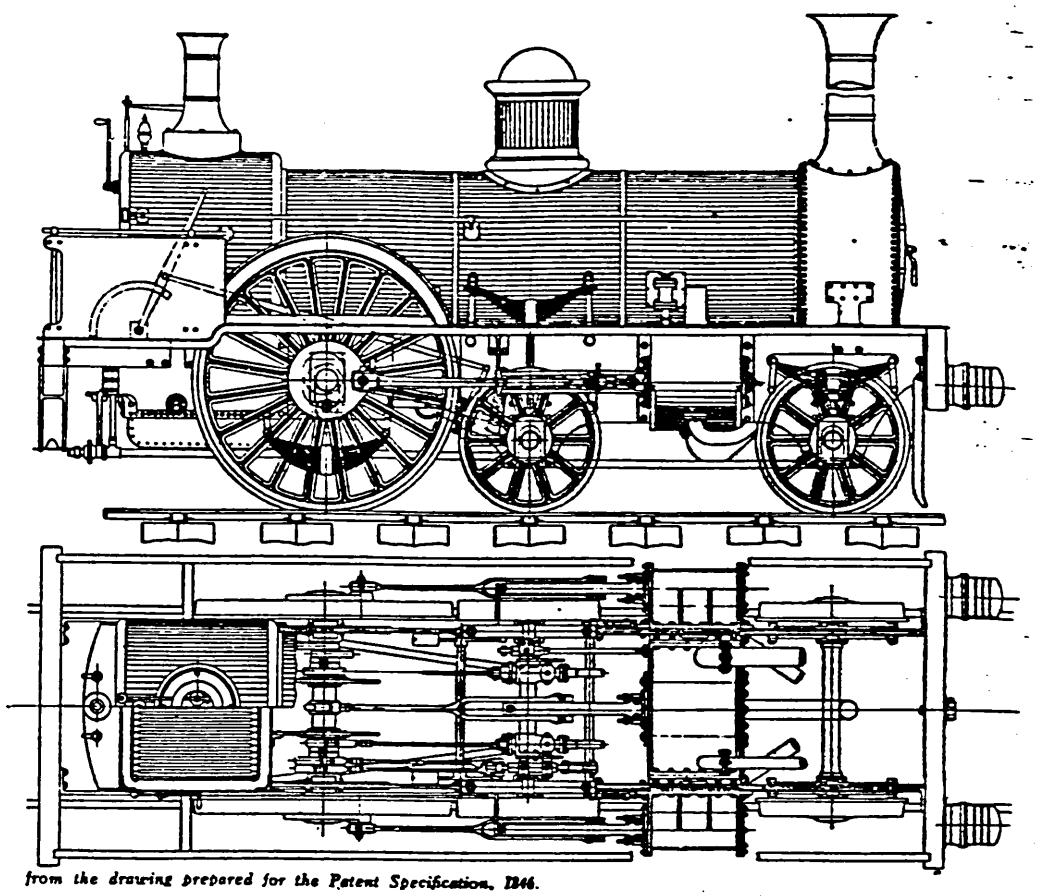


Fig.4.16 G. Stephenson's and W. Howe's three-cylinder locomotive

This design may, not unreasonably be seen as Stephenson's immediate response to the problem of improving the dynamic stability of railway engines. Interestingly, his first reaction was not to adopt the rim balance weights in the driving wheels described by Fernihough and, on a limited scale, being employed by other engineers too. His design to overcome the problem incorporated three horizontal cylinders placed in line across the locomotive and all connected to the single driving axle. The two outside cylinders drove cranks on the same centre, i.e. the pistons reciprocated in unison, and 90 degrees in advance of the inside cylinder. Not only did this arrangement eliminate the rolling motion it also got rid of the 'nosing' tendency as well although it did not diminish in any way the variation in draw-bar pull. The problem was still perceived in terms of the locomotive only with deleterious reactions on the track not entering the consideration.

Ahrons, citing The Times of 29 April 1847, states that one of these engines hauled a train of five carriages the 41 miles from Wolverton to Coventry in 42 mintues.[59] Their steadiness in operation was noteworthy, a fact attested by D.K. Clark and quoted by Warren who also refers to the fact that one of these engines, in a modified form, was usually employed to haul the Royal train between York and Berwick when Queen Victoria travelled on the East Coast route.[60] G.P. Bidder also spoke of their remarkable steadiness but opined that cost and complication prevented adoption of the scheme[61] while T.E. Harrison expressed the view that the locomotives gave no advantage over any other well-balanced engine.[62] At least one

of the two locomotives was rebuilt within a few years, its original 4-2-0 wheel arrangement being modified to a 2-2-2 type.

But whatever the operational merits of these engines, their performance was not such as to lead to the design being perpetuated or developed and, according to Warren, a drawing of Robert Stephenson & Co. of a type of locomotive supplied to the York, Newcastle and Berwick Railway in 1848, shows balance weights in the wheels.[63] Evidently this firm quickly found that the simple compromise of partial balancing by this means was an easier, but acceptable, alternative.

At this period several other patents were taken out for multi-cylinder locomotives[64] but the next significant engine of this type appeared not in England but on the Continent of Europe.

4c. The 'Duplex' Passenger Express Engine

Confronted with the task of providing a new passenger express locomotive for the Austrian State Railway, John Haswell's solution to achieve steady running at express speeds was a four-cylinder locomotive with four cranks on a single driving axle. The following diagram, Fig.4.17[65] shows the principle of operation of the mechanism.

The pairs of outside cylinders on each side of the locomotive were located side by side and connected to a crank and return crank, opposed to each other, so that the two pistons

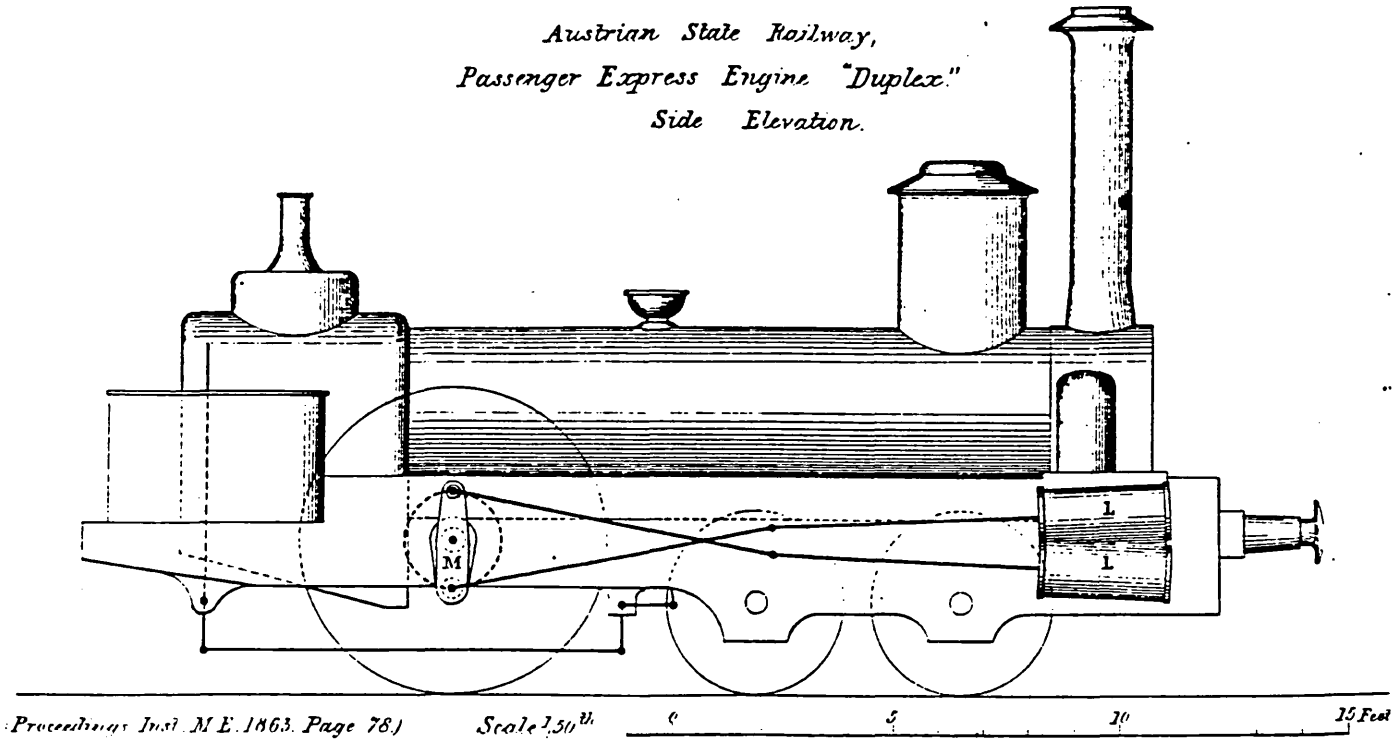


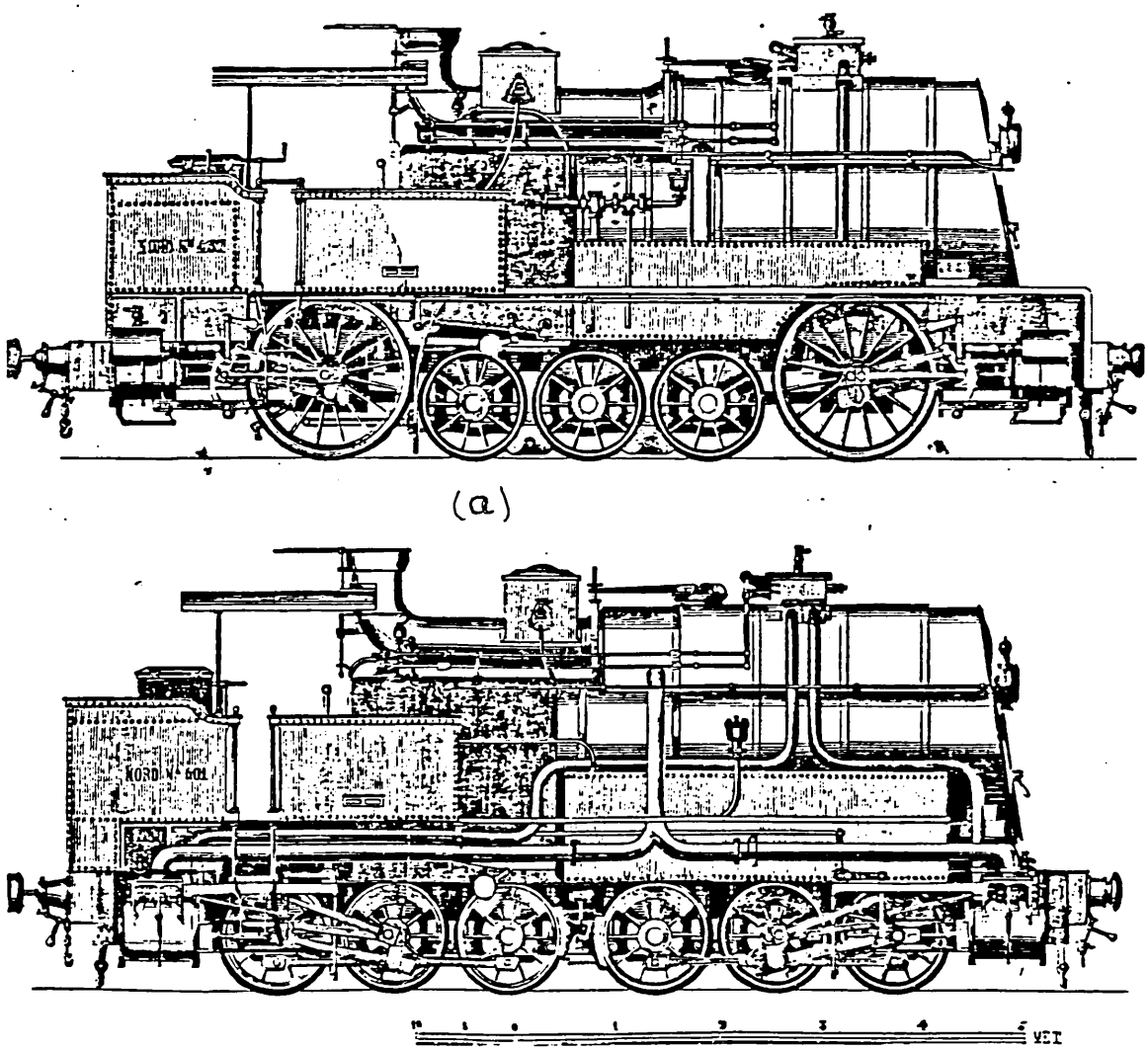
Fig.4.17 J. Haswell's 'Duplex' locomotive for the Austrian State Railway

and their associated driving mechanisms moved in opposite directions. As with Stephenson's three-cylinder engine, this locomotive built in 1861, was acknowledged to possess steadiness at high speeds, and it received considerable attention at the International Exhibition of 1862, but this advantage was obviously not deemed to be of such worth as to build more locomotives of the type. There is certainly little evidence to substantiate Duffy's claim that the design proved to be 'very influential'[66] and D.K. Clark's appraisal of the design, made in 1863, offers a reason for this.

> There can be no question that this system is perfectly successful in effecting the object in view; and had it been brought out twenty years ago, it would no doubt have been highly appreciated. But as the balancing of engines with two cylinders has for the last ten years been completely accomplished for all practical purposes by means of couterweights, the use of four cylinders as in this engine is not likely now to become popular.'[67]

Despite occasional appearances over the following years of multi-cylinder designs to deal with the balancing problem, Clark's pragmatic assessment summarised the almost universal view of locomotive engineers until the machine ceased to be used for railway traction.

Although by the 1860s the destructive effects of 'hammer-blow' on the rails had not been identified the adverse results of running locomotives of ever-increasing size and weight on the track was unmistakable and led to some radical designs to remedy the situation. In this respect French engineers were much more adventurous than their British counterparts and in a sense locomotive practice in the two countries diverged at this period and thereafter developed independently. During November 1866 Engineering reported and illustrated two new French multi-cylinder locomotives. In its issue of 2 November it dealt with the engines, both passenger and goods,



(a)

(b)

Fig.4.18 (a) Passenger locomotive and (b) goods locomotive designed by M. Petiet for the Northern Railway of France

designed for the Northern Railway by its Engineer-in-Chief, M. Petiet.[68] These are illustrated in Fig.4.18. To avoid injury to the permanent way the great weight of these engines was carried by ten and twelve wheels respectively. On the passenger engine four cylinders were used rather than coupling the wheels together whilst the goods engine, in which the wheels were grouped into two sets of six coupled wheels, was also propelled by four cylinders.

Three weeks later the same journal published details of M. Jules Morandière's proposed three-cylinder locomotive for heavy passenger traffic on metropolitan lines.[69] This engine, too, was powered by a divided drive - the front group of wheels being driven by two outside cylinders while the rear wheels were powered by a single inside cylinder beneath the boiler. Fig.4.19 shows this locomotive.

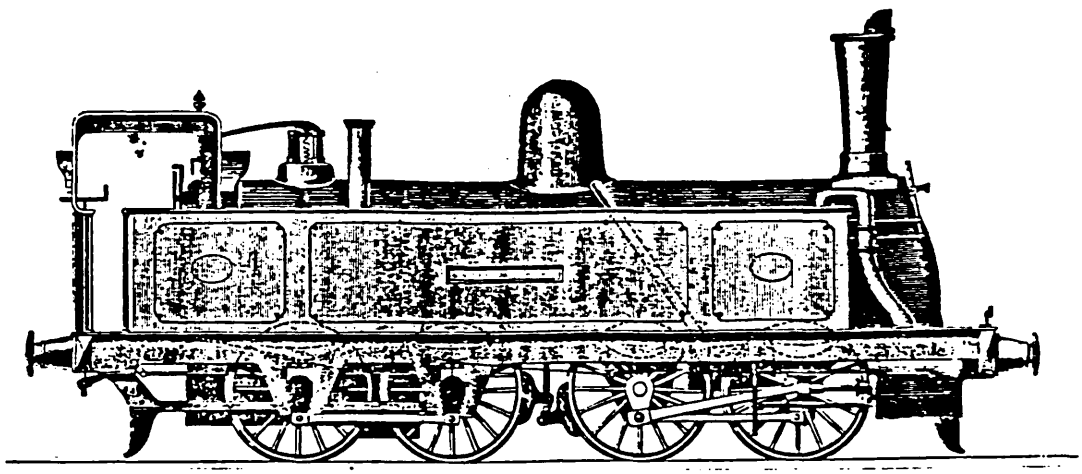


Fig.4.19 M. Jules Morandière's proposed three-cylinder engine

The real significance of these locomotives and the ideas they embodied is not that they were outstandingly successful because, yet again, there is no evidence that their design was perpetrated but rather that their appearance did not give birth to an aversion to multi-cylinder locomotives which characterised locomotive engineering both in Britain and in the United States of America. In the following decade, when compound locomotives arrived on the scene and in general proved faster and more powerful than the simple expansion engines they replaced they earned a reputation and an acceptance which was to persist and fundamentally differentiate French locomotive practice from both British and American. With the much more common use of compound locomotives in France, with the inherent opportunities for better balance, balancing does not seem to have been the perennial problem in that country that it became and remained here.

4d. H.F. Shaw's Four-Cylinder Balanced Locomotive

Notwithstanding the comment in the preceding paragraph concerning American dislike of engines with more than two cylinders, their engineers were no less fertile than their European counterparts in producing new designs. Shaw's locomotive, built at the Hinkley Locomotive Works, Boston, in 1881, may be regarded as the New World's equivalent of 'Duplex'. In this locomotive, shown in Fig.4.20[70] the two horizontal cylinders on either side on the engine were placed side by side rather than one above the other.

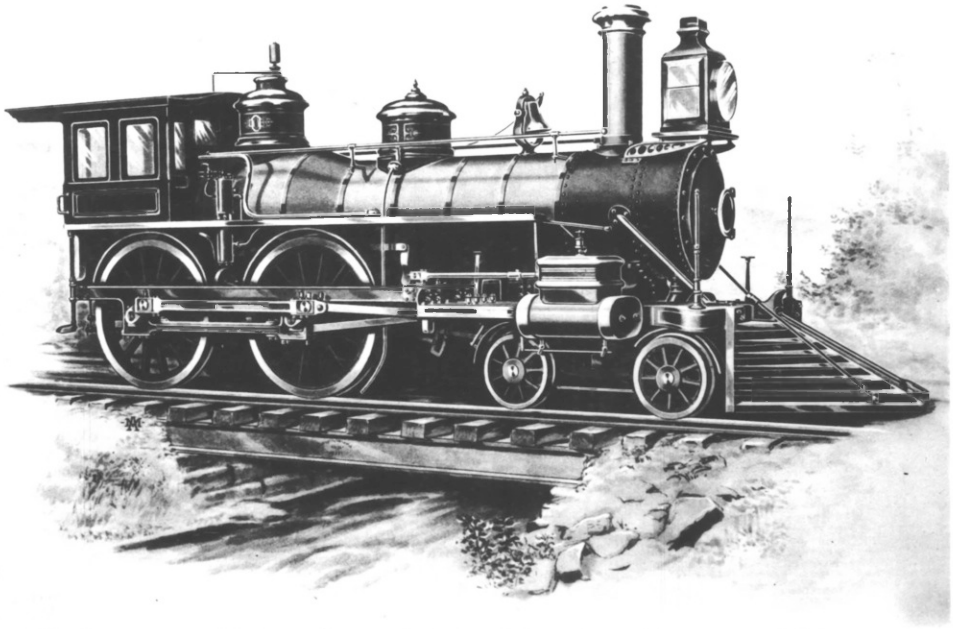


Fig.4.20 H.F. Shaw's Four-Cylinder Balanced Locomotive

The pistons drove crank pins on the wheels diametrically opposite each other and so the inertia forces generated by the reciprocating masses associated with each pair of cylinders were mutually self-neutralising. But this locomotive shared the same fate as Stephenson's and Haswell's. Whatever its merits, and these were fully exploited through lavish advertising and demonstration, the design did not commend itself to contemporary railway officials. Indeed this conclusion applied to multi-cylinder locomotives is generally applicable to the several schemes and expedients considered in this chapter.

When three- and four-cylinder engines did make their appearance in British railway operation it was primarily to meet increased power requirements rather than to improve their

dynamic characteristics.

5. Designs avoiding the use of reciprocating steam engines

A reciprocating piston in a cylinder, with its associated connecting-rod and crank mechanism is hardly a rational design for the production of rotary motion and from the time of Watt's experimental 'steam wheel', built in 1774,[71] numerous attempts have been made to apply the power of steam directly to the generation of rotary motion by means of rotary engines. According to W.J.M. Rankine, by 1878 over two hundred had been patented in Britain alone.[72] With its potential for supplying a uniform continuous power output this type of engine was the ideal propulsive unit for the steam locomotive, obviating the troublesome parasitic disturbances to its smooth running on the track, and it is not surprising that the rotary engine should have engaged the attention of inventors seeking a steadier vehicle. Examination of patent specifications, however, does not enable us to ascertain the extent to which many of these early engineers appreciated the true nature of the vibration problem although, clearly, in the early 1830s both J.G. Bodmer and G. Heaton perceived the effects of the inertia forces generated by reciprocating masses. But where writers or patentees explicitly refer to the avoidance of the reciprocating mechanism we cannot be sure of the reasons. The number of ideas patented for the application of these engines to railway locomotives is relatively small, perhaps the difficulties of making a reliable rotary machine were well known even to amateur inventors, but the actual proposals ranged from the simple to

the utterly bizarre. Direct rotation from steam power was eventually successfully accomplished by the high-speed turbine but to maintain a chronological sequence brief consideration will be given to the scheme of J.A. De Grand to propel the locomotive by steam jet reaction.[73]

5a. The Jet Reaction Steam Locomotive

De Grand's purpose, explicitly stated, was to eliminate steam cylinders, pistons, piston-rods and cranks. In 1838 it was quite possible that he, too, recognised the significance of the inertia forces and in seeking to get rid of these components he was consciously attempting to improve vehicle stability. His proposed design is shown in Fig.4.21. Essentially it consists of three pipes emerging from the top of the boiler and turned into a horizontal direction, two of them backward and the other one forward. Each of these pipes was to be fitted with a valve, to control the flow of steam from the boiler, and terminated in a trumpet-shaped orifice. Of the two nozzles directed backwards, one, f, with a throat diameter of one and a half inches was to be used for short periods, to augment the thrust from nozzle b, during starting and to accelerate the train when required. Nozzle b, with a throat diameter of 0.8 inch, and which De Grand considered to be an

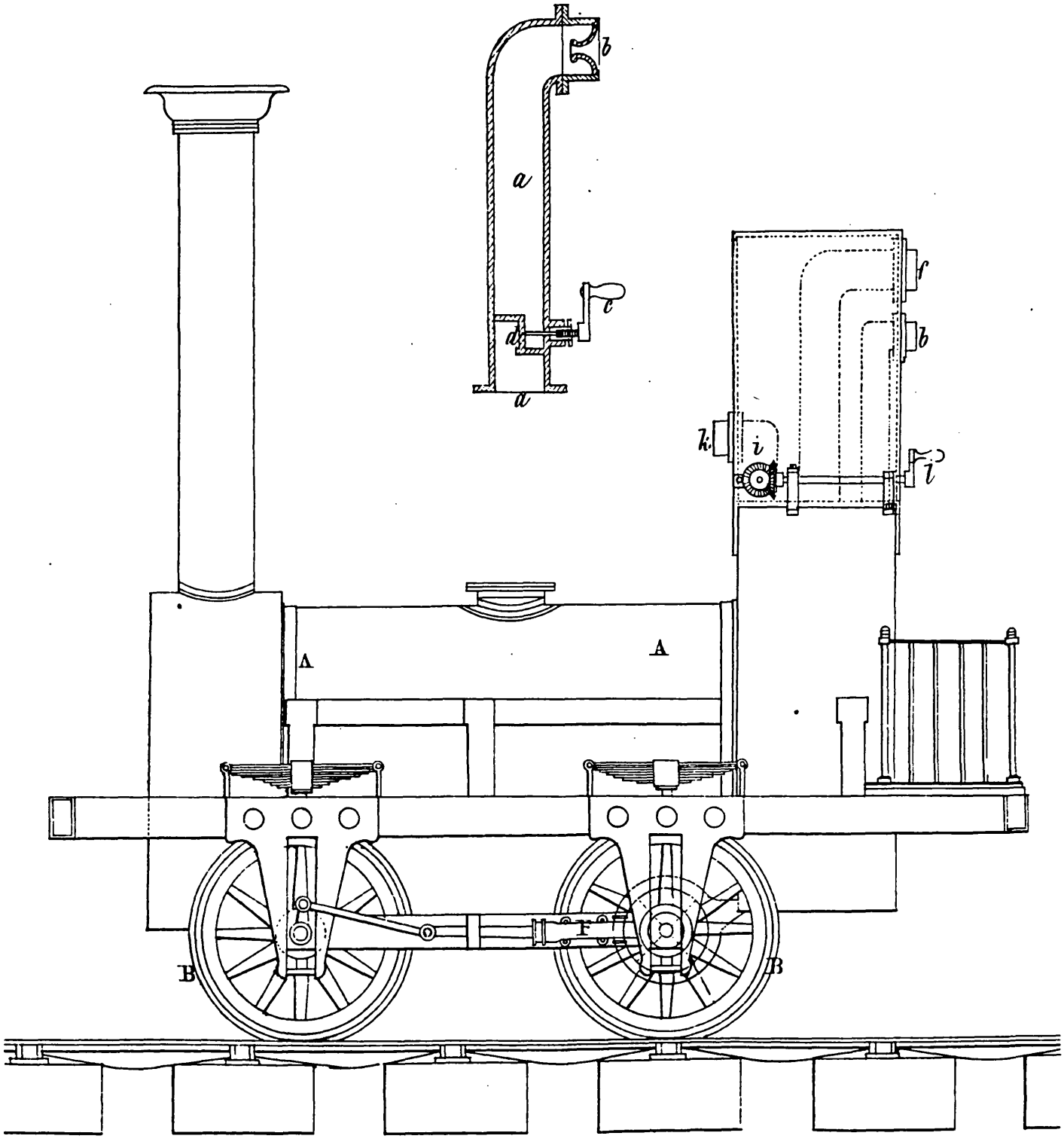


Fig.4.21 The Jet Reaction Steam Locomotive of J.A.E. De Grand

appropriate substitute for conventional locomotive cylinders of 12 inches diameter and 18 inches stroke, was to be used for normal forward propulsion once the train had acquired the desired running speed. The forward-facing orifice was for reverse motion.

An appreciation of the impracticality of the idea is derived from the fact that, at the proposed boiler pressure of 50 psi, the steam jet would issue from the normal propulsion nozzle with a velocity of about 2,300 feet per second and would discharge steam at the rate of around 27,000lb per hour. In other words the evaporative capacity required of the miniscule boiler was that attained by large locomotives such as Bulleid's 'Merchant Navy' Class or the British Railways Standard Class 7, the 'Britannias' over a century later. Additionally, assuming a locomotive weight of ten tons and total resistances to motion of about 30lb per ton this vast consumption of steam would provide just about enough propulsive force to move the locomotive and its tender. However, it is obviously worthwhile making a comparison with what was being achieved in contemporary locomotive performance and Bury's four-wheeled engines of the London and Birmingham Railway had an evaporative capacity of 5,300lb hr^{-1} although larger, six-wheeled, locomotives of the mid-century could evaporate about 10,000lb per hour.[74] But these figures are far removed from De Grand's requirements which were obviously grossly in excess of what could have been provided by the existing state of railway technology.

In leaving this particular locomotive it is also worth observing that the trumpet-mouthed orifices, just above the

driver's head, are not the right shape for efficient operation (they need to have a long divergent section with an included angle of not more than 20°) and would cause the vapour stream to break away from the nozzle walls both increasing the frictional losses and envelop the driver's head in a cloud of scalding steam. In a design apparently so carefully contrived to eliminate the sources of irregular motion it is rather droll to find the inventor resorting to a crank-driven reciprocating feed pump to supply the boiler with water.

5b. Steam-Turbine Locomotives

Indubitably at the end of the nineteenth century the steam turbine made an immediate and what proved to be a permanent impact on the industrial world with its phenomenally successful application to both stationary power-plant, for driving generators, and to marine propulsion. It was inevitable, perhaps, that this development should have stimulated the interest of locomotive engineers who were constantly seeking to improve the thermal efficiency of their engines. And indeed, such was the case.

A number of these machines were built in Sweden, Britain, France, Germany, Italy, Switzerland and the United States of America. Although they gave varying degrees of satisfaction in service none of them could be considered successful in the sense that the experiment was repeated.[75]

From a mechanical point of view the turbine possessed a number of significant advantages over conventional railway locomotives. The absence of reciprocating parts gave a

locomotive that produced no hammer-blow effect on the track at any speed, while rotating balance within the turbine was easily achieved. As a power unit the turbine was relatively compact and offered the advantage of a constant torque output giving a steadier draw-bar pull and thus, from this aspect, it would seem the ideal propulsive unit for the locomotive. The L.M.S.R. Turbomotive, built at Crewe in 1935, was permitted by the civil engineer to have a static axle load of 24 tons maximum compared with 22.5 tons maximum for reciprocating steam locomotives.[76] Small though this additional allowance of 1.5 tons per axle may seem, in the relentless pursuit for more power every such increment was eagerly sought and used to the full by the locomotive engineer because it gave a worthwhile increase in adhesion weight. But this, and the steadier-running engine were advantages of secondary importance here.

The motive power engineers' prime concern was to improve the thermal efficiency and this he was unable to do in a meaningful way because the conditions under which a turbine operated most efficiently, that is, constant load and speed, were not characteristic of railway working.

Additionally, of course, the maximum thermal efficiency was only gained by using the greatest practical temperature range which involved the use of a condenser but railway experience had shown that condensing did not produce a net gain in either power or efficiency because of the extra weight and complications arising from the employment of this piece of equipment. In this respect the turbine locomotives differed in no significant manner from their conventional counterparts. The

necessary additional maintenance work involved and the consequential reduction in operational availability more than offset the economy in coal consumption, although, of course, this could be expected with a single locomotive, the only one of its kind, operating in a system established to cater for an entirely different type of machine. Nevertheless, in performance, the Turbomotive showed little advantage over a conventional reciprocating engine of similar capacity and, operating on standard pressures and temperatures, there was no hope that it could be made to compete on an economic basis. But it must be remembered that the locomotive covered over 300,000 miles in revenue-earning service, a feat unequalled by any other British locomotive of unconventional design. Built as an experimental engine it suffered from its share of customary teething troubles to be anticipated with such enterprises but these problems were not insurmountable and the turbine locomotive, after ten years' service, was predicted to possess potential for future development. In his paper, read to the Institution of Locomotive Engineers in 1946, R.C. Bond summarised his assessment of the position,

> On present indications, the next five years should show up the turbine locomotive in an increasingly favourable light...it is not beyond the bounds of possibility that a limited number of non-condensing turbine locomotives, in a more highly developed form based on the experience with No.6202, will be regularly employed on the heaviest

and fastest express trains, with profit to their owners.[77]

These expectations were not realised. Changed conditions in the immediate post-War years prevented any further work on turbine locomotives and No.6202 was rebuilt as a conventional reciprocating engine. So Turbomotive, like the other locomotives discussed in this chapter, never seriously challenged the traditional reciprocating steam locomotive. Despite its ten years' service (some of them during the abnormal time of war) it never had the opportunity to do so. The envisaged further developments were never carried out.

Similar was the fate of the other engines considered here. They have been selected because they represent a deliberate attempt to produce a well-balanced, steady-running engine. Far from being unique, they are but a tiny fraction of a rich and wide diversity of 'special' locomotives designed over the years to overcome all sorts of problems, both real and imagined, but which were never accepted.[78] The simple, reliable and robust but ubiquitous reciprocating locomotive of conventional design, running in all sorts of systems, from small independent companies to large national networks, did not give any other type the chance to establish itself and survive. Entirely was the infrastructure of the railway industry and its technology committed to the 'standard' locomotive and to serving its needs. In these circumstances the innovative design and the raw prototype, whatever their potential merits, were not given

serious and methodical development but, being considered a nuisance because they did not fit into the system, they were rejected.

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4. Patent No.2599 R. Trevithick and A. Vivian 24 March 1802.
5. Patent No.546 A.W. Makinson and W.F. Batho 28 February 1862.
6. Makinson, op.cit., p.99.
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13. Ibid., p.88.

14. Walker, H.T., 'The Origin of the Balanced Locomotive', The Locomotive, 15 January 1909, p.10.

15. Ahrons, op.cit., p.61.

16. Walker, op.cit., Vol.XV, 15 January 1909, pp.10-12; 15 March 1909, pp.56-58; 15 June 1909, pp.110-113, Vol.XVI, 15 March 1910, pp.58-60; 15 November 1910, pp.246-248.

17. Walker, H.T., 'The Earliest Balanced Locomotives', The Railway Gazette, 6 August 1909, pp.181-183; 13 August 1909, pp.217-220.

18. Patent No.9702 J.G. Bodmer 20 April 1843.

19. Memoir of J.G. Bodmer, Proceedings of the Institution of Civil Engineers, Vol.28, 1869, pp.583-584.

20. Patent No.9702 J.G. Bodmer 20 April 1843.

21. Bodmer, J.G., 'The Advantages of Working Stationary and Marine Engines with High-Pressure Steam, Expansively and at Great Velocities, and of the Compensating or Double-Crank System', Proceedings of the Institution of Civil Engineers, Vol.IV, 1845, pp.372-399.

22. The Railway Gazette, 6 August 1909, p.183.

23. Report of the Gauge Commissioners, Presented to both Houses of Parliament by Command of Her Majesty. Printed by T.R. Harrison, London, 1846. Bodmer's evidence given on Saturday, 25 October 1845, consisted of answers given to questions numbers 4160 to 4218 inclusive.

24. It was not unusual at that period for locomotive manufacturers to build engines of their own design and then with the cooperation of a railway company to try them on that company's lines. According to Clement E. Stretton, The Locomotive Engine and its Development, Crosby Lockwood and Son, London, 1903, p.2, Edward Bury's 'Dreadnought' built in 1830 was tried on no less than five lines and then taken back to Bury's works and broken up. In some cases the railway company subsequently purchased the engines.

25. Report of the Gauge Commissioners, Question No.1323.

26. Ibid., Question No.2210.

27. Ibid., Question No.4294.

28. Railway Chronicle, 10 February 1849, p.84, Correspondent 'H.F.'.

29. Ibid., 3 March 1849, pp.147-148, Correspondent 'H.F.'.

30. Patent No.10243, J.G. Bodmer, 3 July 1844.

31. Report of the Gauge Commissioners, Question Nos.4208 and 4215.

32. The Locomotive, 15 November 1910, p.248.

33. Ibid., 14 February 1931, p.43.

34. Sekon, G.A., The Evolution of the Steam Locomotive, The Railway Publishing Co. Ltd., London, 1899, p.100.

35. Clark, Daniel Kinnear, Railway Locomotives: Their Progress, Mechanical Construction and Performance; with the Recent Practice in England and America, Blackie and Son, Glasgow, MDCCCLX, p.166.

36. Stretton, Clement E., The Locomotive Engine and its Development: A Popular Treatise on the Gradual Improvements Made in Railway Engines Between 1803 and 1903, Crosby Lockwood and Son, London, 1903, p.97.

37. The Engineer, 4 January 1856, p.9.

38. Aspects of George Heaton's work have already been examined in Chapter 2, Section 6.

39. (i) McConnell, J.E., 'On the Balancing of Wheels', Proceedings of the Institution of Mechanical Engineers, 13 June 1848, pp.8-9.

(ii) See also Sekon, G.A., The Evolution of the Steam Locomotive (1803-1898), The Railway Publishing Co. Ltd., London 1899, 2nd edition. Referring to this trial, Sekon gave a confused and grossly erroneous description of the event. According to him McConnell's test was made on the London and North Western Railway with engine No.175, the 'Snake'. Having described Heaton's mechanism, he concluded

> The result was a rude disillusion of the idea, and a complete wreckage of both the theory and the 'Snake', the engine breaking down on its first trip, after being fitted with this reciprocating counterbalance.

Now McConnell did not have any connection with the two 'Snakes' then in existence. The first was a 7ft gauge locomotive on the Great Western Railway while the second built at Nine Elms in 1843 for the London and South Western Railway, ran until 1866. Furthermore, the LNWR

engines with which McConnell was concerned did not have names but only numbers. No.175 was a successful design goods engine built in 1859 (see ref.11, p.63 and also Lowe, James, British Steam Locomotive Builders, Goose and Son Publishers Ltd., Cambridge, 1975, pp.307 and 386). Probably Sekon was confusing this issue with McConnell's large 2-2-2 engine with outside cylinders which was built in 1849. It was slightly out of gauge and various platforms had to be moved back to provide cylinder clearance which earned the locomotive the nickname 'Mac's Mangle'.

Details such as this highlight the difficulties of the present-day historian in using this, and similar 'locomotive histories' as sources of information.

40. The Engineer, 17 March 1882, pp.197-198.

41. Society of Arts, Manuscript Minutes of the Committee of Mechanics for the years 1849-1852. I am indebted to Dr D.G.C. Allan, of the Royal Society of Arts, for permitting me to examine these documents.

42. Ibid., p.19.

43. Yarrow, A.F., 'On Balancing Marine Engines and the Vibration of Vessels', Transactions of the Institution of Naval Architects. April 1892, pp.213-228.

44. Patent No.546, A.W. Makinson and W.F. Batho, 28 February 1862.

45. This drawing is reproduced from the Abridged Patent Specification.

46. Patent No.2813, E.O. Schlick, 8 February 1894.

47. Engineering, 12 April, 1901, p.469. Figs.4.11 and 4.12 are reproduced from this article.

48. The Locomotive, 15 April 1933, pp.109-113, 'The Cossart Rotary Valve Gear'.

49. Ibid., 15 May 1933, pp.140-143, 'New Locomotives for Suburban Service, Northern Railway of France'.

50. Ibid., p.142.

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52. Tolle, M. Die Regelung der Kraftmaschinen, Verlag von Julius Springer, Berlin, 1905, pp.199-200.

53. Ibid., p.199, Fig.180.

54. Patent No.11086 G. Stephenson and W. Howe 11 February 1846.

55. Snell, S. A Story of Railway Pioneers: Being an Account of the Inventions and Works of Isaac Dodds and his Son Thomas Weatherburn Dodds, Selwyn and Blount Ltd., London, 1921.

56. Patent No.8219, I. Dodds and W. Owen, 16 September 1839.

57. Snell, op.cit., p.102.

58. Warren, J.G.H., A Century of Locomotive Building by Robert Stephenson & Co., 1823-1923, Andrew Reid & Co. Ltd., Newcastle Upon Tyne, 1923, p.392.

59. Ahrons, op.cit., p.75.

60. Warren, op.cit., p.393.

61. Makinson, op.cit., p.102.

62. Ibid., p.84.

63. Warren, op.cit., p.394.

64. In 1847, A.S. Livingstone took out a patent, No.11845, for a locomotive in which two cylinders of equal size were placed on each side of the engine '...by which oscillating motion...is prevented'. J. Barber, in 1856 (Patent No.373) and J. Gregory, in 1859 (Patent No.1910) also produced designs for four-cylinder locomotives, while J.W. Clare (Patent No.6, 1858) reverted to opposed pistons in three cylinders to produce a uniform motion.

65. Fig.4.17 showing Haswell's 'Duplex' is reproduced from the Proceedings of the Institution of Mechanical Engineers, 1863, Plate 27.

66. Duffy, M.C. 'Rail Stresses, Impact Loading and Steam Locomotive Design', History of Technology, Ninth Annual Volume, Mansell Publishing Limited, London, 1984, p.58. Duffy does not substantiate his claim that the design of 'Duplex' was 'destined to prove very influential' and appears to contradict himself in his following paragraph where he wrote '...it was not reproduced, probably being thought too complex'. Although he does add an observation that 'the "Duplex" idea was continually revived in different guises until the end of steam traction', but accepting that Haswell's principle, of four outside cylinder locomotives constructed with a pair of self-balancing cylinders on each side of the engine did occasionally appear, generally as a short-lived experiment, it hardly merits the claim of very influential.

67. Clark, D.K., 'On the Locomotive Engines in the International Exhibition of 1862', Proceedings of the Institution of Mechanical Engineers, 1863, pp.78-111. See pp.97-98 for Clark's comments on 'Duplex'.

68. Engineering, 2 November 1866, p.334. Fig.4.18 is reproduced from this issue.

69. Engineering, 23 November 1866, p.392. Fig.4.19 is reproduced from this issue.

70. Alexander E.P., 'Iron Horses' American Locomotives 1829-1900, W.W. Norton & Co. Inc., New York, 1941. Fig.4.20 is reproduced from this book, p.189.

71. Dickinson, H.W. and Jenkins, R., James Watt and the Steam Engine, Moorland Publishing Co. Ltd., Ashbourne, 1981, p.146.

72. Rankine, W.J.M., A Manual of the Steam Engine and Other Prime Movers, Charles Griffin & Co., London, 1878, 9th Edition, p.504.

73. Patent No.7903, J.A.E. De Grand, 12 December 1838.

74. Reed, Brian, 150 Years of British Steam Locomotives, David & Charles, Newton Abbot, 1975, p.51.

75. An exception to this statement is probably justified in the case of Swedish experience on the Grangesberg-Oxelosund Railway because having operated its first locomotive of this type from 1930 it obtained another two in 1936 and they remained in service until electrification in 1954.

76. Nock, O.S., The British Steam Railway Locomotive 1925-1965, Ian Allan Ltd., London, 1983, p.113.

77. Bond, R.C., 'Ten Years' Experience with the LMS 4-6-2 Non-Condensing Turbine Locomotive No.6202', Journal of the Institution of Locomotive Engineers, Vol.XXXVI, 1946, p.223.

78. Ernest F. Carter's Unusual Locomotives (Frederick Muller, London, 1960) is devoted to this theme and surveys a number of locomotives, from the very beginning of railway traction to Bulleid's 'Leader' engine almost at the end of the steam era. More specifically, J. Dunlop's series of articles 'The Balancing of Locomotives' published in The Mechanical Engineer, February-April 1912, also reviews several locomotives in this category.

Chapter 5

THE MISSED OPPORTUNITY

By the end of the nineteenth century several stimuli to the development of more powerful locomotives had occurred. Of fundamental importance was the increase in traffic, especially the passenger side of the business. Since 1872, when both the Midland and the Great Eastern Railways started to carry third-class passengers on all trains, and began a movement which gradually grew, the number of passengers per year increased by a factor of 2.74 to a total of 1,114,600,000 in 1900.[1]

Not only were more passengers carried but they were conveyed in greater comfort, with the railway companies competing for more custom through the provision of better, in some cases luxurious, accommodation; cheap fares, excursions and so on. The facilities provided were certainly of benefit to the travelling public and, on the evidence of the immense growth in the volume of passenger traffic, were appreciated. Pullman cars, sleeping-cars and dining-cars successively made their appearance and met the apparently insatiable needs of the people. Early trains were provided with breakfast cars and no long-distance train was considered properly equipped without at least one third-class dining-car. However, the era of the dining-car did not really begin until 1892 when the Great Western Railway introduced the first complete corridor train. The primitive conditions and hardships of travel in earlier years were rapidly giving way as the amenities and comforts of gracious living were becoming an integral part of the railway service. These developments euphorically welcomed by George

Montagu, who regarded progress at the turn of the century to be '...perhaps the most important, at any rate the most interesting period in the railway history of this country',[2] were seen in a somewhat different light by Clement Stretton, another commentator on the railway scene.

An obvious and profound consequence of the provision of all these amenities was that the weight of trains became much heavier and in the case of long-distance trains this increase was quite out of proportion to the number of passengers carried. Indeed, the corridor coach reduced the carrying capacity of the vehicle. This trend increased operating expenses and reduced profits and, therefore, was hardly likely to be viewed with satisfaction, much less pleasure, by shareholders and more economically-conscious students of the transport system. By the time, December 1902, he had written the Preface to the Sixth Edition of his book on the development of the steam locomotive Stretton provided details to substantiate his claim that the machine had become '...an expensive and extravagant appliance'.[3]

Whereas the express train of 1875, with an engine and tender weighing about 55 tons, hauled a train of about 150 tons, at an average speed of 43-46 mph with a coal consumption of 18-22lb per mile, the contemporary express with a locomotive and tender weighing 100 tons, drew a train of some 320 tons at 53-60 mph with a coal consumption of 40-56lb per mile. However, the increased working expenses of the modern express were not met by a greater paying load, the reverse was the case, for it carried fewer passengers and took less receipts per mile than its counterpart of 1875.

Stretton's view of locomotive development was certainly less enthusiastic than Montagu's and in noting that the present-day locomotive and tender required more steam, coal and water to propel themselves alone than was needed by the entire engine and train in 1875 he questioned the rationality of hauling 100 tons of prime mover at the head of a train when electric traction could achieve the same result with 'two conductors'.

Regardless of the views of contemporary observers, the sentiments of these two writers representing, perhaps, the range of outlook allowed by the situation, the implication of these innovations for the design of express passenger locomotives is unmistakable.

The railway races of 1895, between London and Aberdeen, over the East and West coast routes, a contest made possible by the opening of Sir Benjamin Baker's Forth Bridge in 1890, gave the railway companies a new appreciation of the possibilities of improving train services. Accomplishment of this was to be achieved by increasing the distances between stops, permitted by the installation of water troughs enabling the train to pick up water when travelling at speed, and running at higher speeds. A prerequisite of this development was, again, more powerful locomotives.

Simultaneously, the growth of suburban traffic was coped with by increasing the number of trains and the frequency of services in addition to making trains heavier by enlarging the coaching stock, in some cases to the limit of the loading gauge, and increasing the accommodation per compartment from ten to twelve passengers. Also the number of carriages per train went

up, reaching a limit only when the length of the train equalled that of the platform. More frequent trains meant greater rates of acceleration and heavier trains to be hauled both led to the requirement of engines of greater power.

It is against this background that J.F. McIntosh's 'Dunalastair' 4-4-0, introduced on the Caledonian Railway in 1896, is regarded as the locomotive 'that began the big-boiler high-output era on British Railways'.[4] A trend confirmed shortly afterwards with the appearance of the large Atlantics of H.A. Ivatt (1898) and J.A.F. Aspinall (1899).

1. Multi-cylinder propulsion

The need for bigger and more powerful locomotives led to a consideration of exploring the possibilities of multi-cylinder propulsion and speculation on the suitability of four-cylinder engines for working heavy traffic was considered to be a topic 'which possesses daily increasing interest' as early as 1866.[5] This need for more powerful locomotives meant that the inside-cylinder arrangement, so much favoured by British railways during most of the nineteenth century, gave way to the outside-cylinder design. Restricted space between the frames limited the potential for increasing the power output by enlarging cylinder sizes. The alternative of securing greater piston thrusts by raising the working steam pressures was not an option considered seriously at the time. Exceptionally, G.J. Churchward, adopted a pressure of 225lbf in^{-2} on his very successful four-cylinder Atlantic locomotive 'North Star' as early as 1906. This remained the standard pressure for all

large main line locomotives on the Great Western Railway until 1927 when it was raised to 250 lbf in^{-2} for the new class of 'Kings'. On one hand the advent of superheating, which significantly raised the thermal efficiency of locomotives, and consequently pleased and satisfied their engineers and operators, was accompanied by steam loss until efficient piston-valves were developed. And on the other hand satisfactory motion parts necessary to transmit bigger thrusts depended upon better materials if scantlings were not to be unduly increased, and this possibility was not to be realised until the 1920s when alloy steels became constructional materials available to locomotive designers.

Progress in achieving greater power was through the adoption of multi-cylinder propulsion. That is, in the design and building of locomotives with three or four cylinders. Despite the occasional proposal for, or appearance of, such machines during the nineteenth century - and Stephenson's, Haswell's and Shaw's engines have been mentioned earlier -multi-cylinder locomotives only became an established feature of British railway operation during the early years of the present century. Although a serious interest in their possibilities can be dated to the late 1890s.

2. The First Four-Cylinder Locomotives

In examining this relatively widespread introduction of multi-cylinder engines it must be constantly borne in mind that the reason for this progression on the part of the larger railway companies was first and foremost the demand for more

power. However, this requirement had to be balanced against other considerations, mainly of an economic nature, and in no sense can the exercise be seen as a conscious, deliberate step to improve the behaviour of locomotives either in terms of improving their unsteady pull on trains or to reduce the hammer-blow effects on the permanent way. The opportunity that the development offered for better balancing was incidental and as such seems to have been recognised and acted upon with varying degrees of awareness, competence and success.

But having acknowledged this it must also be conceded that the opportunity for achieving better balance brought immediate and important practical consequences not only in terms of the locomotive and its train but also with respect to that part of the railway system that came under the aegis of the civil engineer. The history of railway operation from a technical point of view provides repeated examples of conflicts between civil and mechanical engineering departments of railway companies. To protect and preserve the permanent way and underline bridges and hence minimise maintenance and replacement costs the civil engineer imposed what he regarded as reasonable loading limits on the track whilst the locomotive engineer, to meet the persistent demands for more power, in general contributed to the immutable evolution of the species by producing a larger and heavier variety. Normal, efficient operation of the system dictated a system of weight restrictions, of course, because economically or technically it would never have made sense, nor was it seriously contemplated, to use the large, heavy, powerful express locomotives on minor

routes and branch lines. Dynamic augment, or hammer-blow, on bridges could be more important than dead weight although, as will be seen later, its significance was not perceived at the time. It was simply a fact that the conventional practice of balancing two-thirds of the weight of reciprocating parts in two-cylinder locomotives imparted a severe dynamic augment to the rails and the bridges over which the engine passed.

A better inherent balance was attainable with the use of three or four cylinders permitting a considerable reduction in the magnitude of the balance weights with as a consequence, and a bonus, the opportunity to increase locomotive axle-loadings without a corresponding deleterious effect on the vibrational behaviour of bridges. Diminution of the hammer-blow characteristics of a locomotive also improved the operational versatility of the engine by increasing its route availability.

In 1897 there appeared three four-cylinder, simple-expansion, locomotives: one to the design of James Manson for the Glasgow and South Western Railway, the second due to F.W. Webb for the London and North Western Railway, whilst the third, the responsbility of Dugald Drummond, designed on the unpredictable 'split-drive' arrangement known as a 'Double-Single', was built for the London and South Western Railway. However, none of these can be regarded as particularly influential as forerunners of multi-cylinder locomotives in this country because the designs were not repeated, and Webb's engine which started life as a 'simple' named 'Iron Duke' in June 1897 was converted into a four-cylinder compound the following May and renamed 'Diamond Jubilee'.

Precise and detailed reasons for the innovative steps taken by these engineers in radically departing from the standard two-cylinder design cannot be determined but the very fact of their doing so is indicative of a perceived need which they felt could not be met by existing practice. Confronted with the evidence that neither Manson nor Drummond pursued the development of this type of locomotive perhaps it is not unreasonable to conclude that the anticipated advantages did not meet their expectations. With his well-known attachment to compound working it is rather surprising that Webb should have entertained the idea of simple-expansion at all. Quite likely it was no more than a comparative test, an idea confirmed by E.L. Ahrons,[6] and its brevity suggests, again, that it was deemed lacking in scope for future exploitation and utilisation.

Opportunities for achieving better balance of the reciprocating parts, and hence obtaining a more smoothly running locomotive less damaging in its effects upon the track and on the underline bridges, came with the introduction of three and four-cylinder locomotives. As Stephenson had shown many years earlier a three-cylinder engine is much easier to balance than the conventional two-cylinder locomotive, while both Haswell in the 1860s and Shaw in the 1880s had clearly demonstrated that a four-cylinder locomotive could, and in their engines did, virtually balance itself. From a dynamical point of view there was a strong case for using more than two cylinders when high-speed running was an operational parameter.

Manson's design[7] possessed the potential for a beneficial exploitation. It placed the four cylinders in line

across the front of the engine and all driving the leading coupled axle. On each side of the engine adjacent cranks were at 180 degrees while one pair of cranks was at 90 degrees to the other pair, thus giving four equally-spaced cranks. This design layout of all four cylinders driving one axle was of fundamental importance in optimising balancing arrangements within the locomotive because its use permitted the reciprocating components to work as opposed pairs and thus eliminated the need for balance weights in the driving wheels to compensate them.

Later, this 'single-axle' drive was used to great effect by C.J. Bowen Cooke in his 'Claughton' class locomotive, despite the possibility of imposing bigger bending moments on the crank axle than occurred with the 'divided drive', the design avoided the transmission of balancing forces through the axleboxes which led to a complete elimination of hammer-blow and produced a smoother running locomotive. In his simple-expansion engine referred to above and also in his compounds of 1897 F.W. Webb balanced each inside crank by extending the crank-arms on the opposite side of the axle to form balance weights, thus avoiding the bending moments created by the load on each crank with the associated balance weights in the wheels.

The evidence considered so far suggests that the engineers concerned made some conscious attempt to secure better balance but D. Drummond's locomotive of the same year, i.e. 1897, indicates otherwise. The two pairs of driving wheels were not coupled but were independently driven, the front wheels by the inside cylinders and the rear wheels by the outside cylinders. From the aspect of balancing it was almost certainly

worse than, and by any reckoning no improvement on, a two-cylinder engine. Writing on this feature of the locomotive E.L. Ahron's summarises its dynamic characteristics thus,

> Although it had the advantages of dividing the power between two axles...it had the disadvantage of irregular turning moment, and also of irregular balancing effects, owing to the absence of coupling-rods.[8]

Shortly after its construction this engine had to have its cylinders replaced by smaller ones and, later, a large boiler was fitted again suggesting that other aspects of its design were not approached rationally.

Reference has already been made to the impossibility of indefinitely increasing the power rating of inside-cylinder locomotives because of restrictions on cylinder diameter. A similar argument was applicable to outside-cylinder engines, the constraining factor in this case being the height of station platforms which again set definite limits on the maximum size of cylinder and, consequently, power. Thus, in British railway engineering the demand for more power at the beginning of the twentieth century had to be met, by those committed to simple-expansion working, by employing more than two cylinders.

3. The 'Decapod'

To meet both the needs of rapidly growing suburban commuter traffic and to demonstrate that steam could compete with electric traction on these busy services, J. Holden built a

0-10-0T (The 'Decapod'), Fig.5.1, for the Great Eastern Railway, at the end of 1902. Described by W.O. Skeat as 'one of the most remarkable steam locomotives ever designed' he also precisely stated the magnitude of the transport problem facing the Great Eastern,

> The number of persons using the Liverpool Street terminus daily was 220,000, about twice as great as the next busiest station, which was London Bridge, used by about 110,000 persons daily. Moreover Liverpool Street had only 18 platforms, but even so it managed to deal with about double the number of daily passengers recorded at the world's largest railway terminus, the Grand Central at New York, with its double-deck layout and 42 platforms.[9]

Technically, it was claimed that an electric train of 315 tons could be accelerated from rest to 30 mph in 30 seconds and Holden was set the task of matching this performance. To secure the necessary power three cylinders were adopted with the cranks equally spaced at 120° (the first time that this crank arrangement had been used) to give the uniform turning moment necessary for smooth and rapid acceleration. This accentuated the compromise nature of the balancing problem because to give the desired acceleration to the train it was necessary to produce a uniform maximum draw-bar pull which demanded total adhesion with minimum variation in wheel-rail contact pressure. (A concomitant of this was good balance because variation in

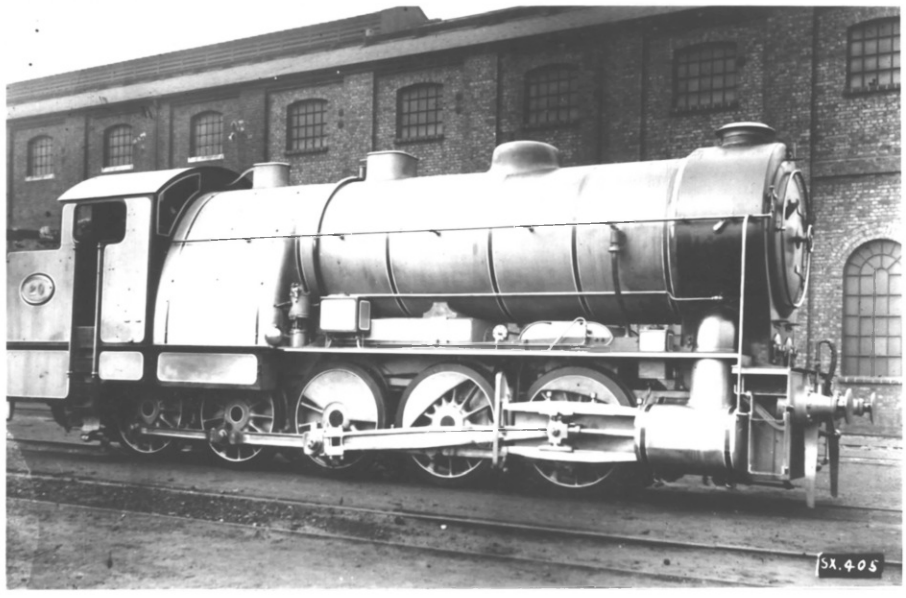


Fig.5.1 The 'Decapod', Great Eastern Railway, 1902

wheel-rail contact pressure would adversely affect the essential total adhesion.) To avoid the vertical component force which would have arisen from the inclination of the central cylinder a horizontal position was adopted for this, necessitating a

special design of connecting rod and leading axle, the design of these components being the subject of a patent taken out jointly by J. Holden and F.V. Russell.[10]

The size of their task and the significance of their result was concisely and lucidly expressed by W.O. Skeat, fifty years later, when in his Newcomen Paper he wrote

> This would be "a tall order" for any locomotive engineer today. ...the seemingly impossible demands were not only triumphantly achieved, but were even exceeded.[11] It was a magnificent experimental effort and a mechanical engineering tour de force of the first magnitude, yielding results which have never been surpassed in the history of steam traction on railways.[12]

The great magnitude of the reciprocating masses made balancing a critical issue, demanding considerable attention. Convention was abandoned and the entire reciprocating masses were balanced instead of the customary two-thirds, the balance weights being distributed, as far as possible, equally between all the wheels.

Such a departure from normal practice elicited the following comments from The Engineer:

> ...the conditions are so peculiar that although careful calculations have been made, the balancing must be regarded as in a measure tentative.[13]

Promptly, from Stratford, came Holden's reply

> The calculations for these weights were most carefully worked out in my drawing office; data was also supplied to a gentleman well known to many readers of your paper as an expert in balancing. He was in America at the time, from which place he posted his result. No other communication was made, and the two final results although worked out by two different methods, were practically identical.[14]

No doubt because of the unusual nature of the enterprise not only did Holden and Russell give especial attention to the balancing themselves but they also deemed it worthwhile to have the matter checked by an independent 'expert', even if it meant transatlantic communication to do so. Unnamed by Holden, the expert, according to W.O. Skeat[15] was Professor Dalby, who also many years later checked the balancing calculations and diagrams, carried out by the use of his own method, for Gresley's A1 Class Pacific.[16] Occasionally locomotive engineers did seek independent expert confirmation of their balancing arrangements or advice on the matter but the scant evidence of such occurrences permits the generalisation that practice of private consultation was unusual. However, as subsequent discussion will indicate, since many engineers were unaware of the results of their balancing designs, for good or ill, the possible benefits of such assessment were simply not perceived.

While 'Decapod' was being built the circumstances which

called it into existence started to change, that is, passenger traffic instead of continuing to increase annually as it had during the 1890s began to drop off. The Great Eastern, like all the other London suburban train services (and, indeed, the railway system nationally) was beginning to feel the competition of the new electric tramways and motor-bus services. Plans to strengthen bridges, necessary for 'Decapod's' regular service use, were abandoned as, too, were any further thoughts of electrification. The need for a locomotive of the power and capacity of Holden's masterpiece had already passed. Because it never went into revenue-earning service and was scrapped after a few years, it has not received the attention it appears to deserve from the locomotive historian. 'Bizarre' is an adjective that such a knowledgeable and restrained historian as B. Reed has considered not inappropriate to apply to 'Decapod' and in the sense that the design unquestionably broke with conventional practice this is understandable. In another, and perhaps more significant way, it is not. This interpretation is as traditional as the whole process of locomotive design throughout almost its entire history and it fails to recognise the potential for future development. The design clearly and convincingly demonstrated that in the hands of an enterprising and innovative engineer, prepared to break with custom, the steam locomotive was capable of meeting extraordinary demands for performance. More specifically from the point of view of this study the episode indicates that at the beginning of the century, with careful analysis of the problem and due consideration given to all the pertinent factors to establish

the appropriate priorities, it was possible to put a heavy, high-powered locomotive into service without unacceptable consequences for the track.

4. The Designs of G.J. Churchward and Sir Vincent Raven

The real precursors of multi-cylinder simple expansion locomotives in Britain were G.J. Churchward's four-cylinder, 'North Star', Fig.5.2, which was built at Swindon in 1906, and Sir Vincent Raven's three-cylinder 'Z' class which appeared in 1911.

'North Star' originally built as an 'Atlantic' (4-4-2) was immediately followed by a batch of ten 4-6-0s and thus was born the famous GWR 'Star' Class which continued in production from 1906 until 1923, when C.B. Collett - Churchward's successor as C.M.E. at Swindon - introduced an enlarged version, the 'Castle' Class which was built until 1950. A short-lived progression from the 'Castles' were the 'Kings' of which class 30 engines were constructed between 1927 and 1930. Thus the four-cylinder, 4-6-0 basic design which was adopted by Churchward in 1906 was perpetuated for almost half a century transcending the Grouping of 1923 and surviving the demise of the GWR itself when it was absorbed into British Railways upon nationalisation on 1 January 1948.

G.J. Churchward's awareness of locomotive engineering on an international scale and his willingness to accept, adapt and develop new ideas is a characteristic of the man generally acknowledged by all railway locomotive historians. In this may be detected the germination of his interest in multi-cylinder



Fig.5.2 'North Star', Great Western Railway, 1906

engines. His importation of the four-cylinder 4-4-2, de Glehn compound 'La France' in October 1903 is well known. But he did not adopt compound working although he accepted the four-cylinders, adapted them to simple expansion and, as just mentioned, they remained a feature of Great Western express passenger locomotives for as long as the Company existed.

M. Edouard Sauvage,[17] speaking of compounds in his papers to the Institution of Mechanical Engineers had emphasised that the division of the drive between the two coupled axles reduced the loading due to piston thrust on the axle-boxes. An expected advantage of this was an increased mileage between general repairs and also an improvement in the riding qualities of the locomotive, compared with a two-cylinder engine, because of the improved balance attainable with four cylinders. The rough-riding that developed with mileage in locomotives with two outside cylinders was a common feature of their behaviour and had been attested by witnesses before the Gauge Commission. With the development of long-distance passenger expresses at this time Churchward was particularly interested in having smooth-riding locomotives and it is in the discussion on the second paper that we find his emerging ideas on the introduction of four-cylinder locomotives.

Although the use of four cylinders makes it possible to eliminate the dynamic augment completely, this is not achieved automatically and a number of factors have to be taken into account. Churchward, working from the divided drive, and to keep both the inside and outside connecting rods of equal length (necessary to maximise the effects of balancing) positioned the

inside cylinders over the leading axle of the bogie and the outside cylinders over the rear axles of the bogie. A proportion of the reciprocating parts for the inside cylinders was balanced in the leading coupled wheels while for the outside cylinders the balance weights were applied to the middle pair of coupled wheels. This procedure, while giving a relatively small hammer-blow for the whole engine, since the balances applied to the two axles concerned were in opposition, did not minimise the hammer-blow from the axles individually. Indeed, they produced a hammer-blow which exceeded that of the two-cylinder locomotives of the 'Saint' class. Thus the opportunity to secure a real improvement had been missed. Caution is necessary here and it is important when studying the nature of the collaboration between locomotive superintendents and civil engineering departments. In this particular case, but seemingly generally typical of conditions elsewhere - as will be seen later in this chapter, it was minimal, indeed virtually non-existent. The opposition of the balance masses applied to the two driving axles concerned gave good balance in the horizontal plane and the 'Stars', Fig.5.3, ran very smoothly. They were clearly superior to the 'Saints', Fig.5.4, and their performance was such as to satisfy the locomotive engineers and the operating departments. Subsequent events indicate either that a full analysis of the balancing design had not been made, the most likely explanation, or, following a complete investigation the vertical forces generated were ignored. It appears reasonable to conclude that all the possibilities of the situation were just not appreciated at the time nor for many

years afterwards. Only as a result of the work of the Bridge Stress Committee were the actual results of the balancing arrangements of the 'Stars' laid bare. Immediately a revised method was adopted by the Great Western Railway and the offending locomotives rebalanced. That one of the major railway companies of the country should perpetuate bad practice when better practice, with its inherent advantages, was a distinct possibility is indicative of an unquestioning, routine approach to locomotive design with no real understanding of the theory of balancing nor an appreciation that expertise could be utilised.

Undoubtedly, Churchward's conversion to four-cylinder propulsion derived from his experience with the de Glehn compounds and his adaptation of the divided drive to his simple expansion 'Stars' established the norm, for Great Western locomotive engineering, of four-cylinders with a divided drive. Thus, this Company had many of these engines but no three-cylinder locomotives.



Fig.5.3 G.W.R. 4 cylinder 'Star' Class Locomotive



Fig.5.4 G.W.R. 2 cylinder 'Saint' Class Locomotive

Experience on the northern lines laid the foundation for a different standard. The G.N.R. had three four-cylinder compounds built in the period 1905-1907, one of which could be worked either simple or compound. Two of these were later converted to two-cylinder simple expansion locomotives. On the N.E.R. two four-cylinder express engines were built by W. Worsdell in 1906, presumably for experimental purposes, but compounding obviously showed no convincing advantage and E.L. Ahrons states 'Though these engines have been very successful, they have not been repeated, and the three cylinder simple engine has become standard.'[18]

This standard originated with Sir Vincent Raven's 'Z'

class, three-cylinder, 4-4-2, locomotives the first of which were built by the North British Locomotive Company in 1911, and the class continued in production until 1917. Continuing the trait, Gresley produced his three-cylinder 2-8-0 coal engine in 1918, his '1000' class Moguls in 1920 and the trend was fully confirmed with the appearance of his A1 Class Pacifics in 1922.

By the time Grouping was imposed upon the railway system of the country in 1923 the basic design preferences of the four large companies were marked by distinct regional differences.

While the G.W.R. did not have any three-cylinder locomotives, the L.N.E.R. did not have any four-cylinder engines (excepting a few experimental engines and a few inherited from the Great Central Railway, e.g. J.G. Robinson's 'Lord Faringdon' Class). The L.M.S.R. which, with the locomotive stud of the Midland Railway, acquired a significant number of three-cylinder compound engines continued to build and operate this type of engine (unlike the other railways). But during the 1920s and 1930s it built both three- and four-cylinder locomotives as did the Southern Railway.

This situation arose from personal opinions moulded by the results of experiments, not always comparative, or from satisfaction with an established practice, which in turn could formulate the whole design philosophy of an engineer. Ultimately it depended upon the nature and character of the man and the constraints within which he had to discharge his responsibilities. Churchward's receptiveness to new ideas has been noted already and its antithesis has been noted by E.S. Cox.

> Whereas Hughes sought however imperfectly to ascertain the best, to Fowler and Anderson all that was Midland was already automatically the best.[19]

It was within these deliberately and consciously chosen parameters of three- or four-cylinder engines that the optimisation, or otherwise, of balancing must be sought rather than between them. Thus the G.W.R. only had the opportunity to make the best use of four-cylinder designs while the L.N.E.R. was constrained by its adherence to three-cylinder layouts. Only in the two companies that used both could a genuine appraisal of the suitability of one arrangement as opposed to the other for any specific application be made. And there is little evidence to indicate that a choice was made on a consideration of balance alone. Nor is this surprising. A successful locomotive was a revenue-earning machine whose value to the company was measured by its ability to do a maximum amount of work for a minimum overall cost. However, there was not a universally acceptable method of determining this and so ultimately the matter resolved itself into satisfying the engineers concerned.

5. The Preference of H.N. Gresley for Three-Cylinder Locomotives

In control of locomotive engineering following the Grouping H.N. Gresley had his feet firmly on the traditional ground of the G.N.R. and the N.E.R. in favouring three-cylinder

engines. Unlike Churchward who, when the necessity for more than two cylinders arose - and with some hesitancy he acknowledged that that situation was imminent in 1904 -unhesitatingly adopted four cylinders, Gresley subscribed to the philosophy of simplicity in terms of meeting power requirements with a minimum number of parts. He was of the school that believed

> ...It is sound engineering to hold that every piece added to a machine, after it has reached the practical stage, is a source of weakness.[20]

This view was predominant throughout the history of the steam locomotive and those of the opposite outlook, who thought that progress was often achieved by complication were not, in general - despite the few notable exceptions of such outstanding engineers as George Churchward, and later, André Chapelon - the most successful or influential, although with hindsight, it is possible to conclude that their approach was the more objective and rational. Nor were those of the 'simple' school consistent in their behaviour for as de Glehn pointedly reminded the critics of the four-cylinder divided and balanced compound engine, because of its complexity, the automatic air-brake, far from being simple, was very complicated and yet they were happy to have it.[21]

Gresley's views on the subject pronounced from his two positions of eminence within his profession, the Chief Mechanical Engineer of the L.N.E.R. and Member of Council of the

Institution of Mechanical Engineers, were given in his paper 'The Three-Cylinder High-Pressure Locomotive',[22] delivered to the Institution at its Summer Meeting at Newcastle-on-Tyne in July 1925.

While referring to a number of four-cylinder locomotives which had proved satisfactory, so far as turning effort was concerned they were little better than two-cylinder engines and distinctly inferior to three-cylinder engines, with their cranks at 120°, in this respect. This was illustrated by the following diagram, Fig.5.5.

The paper described tests carried out with two- and three-cylinder express passenger engines of similar type and power, and likewise, with 2-8-0 type mineral engines.

By means of a series of diagrams, Figs.5.6[24] and 5.7[25], of characteristic draw-bar pulls the steadier pull of the three-cylinder engines is shown.

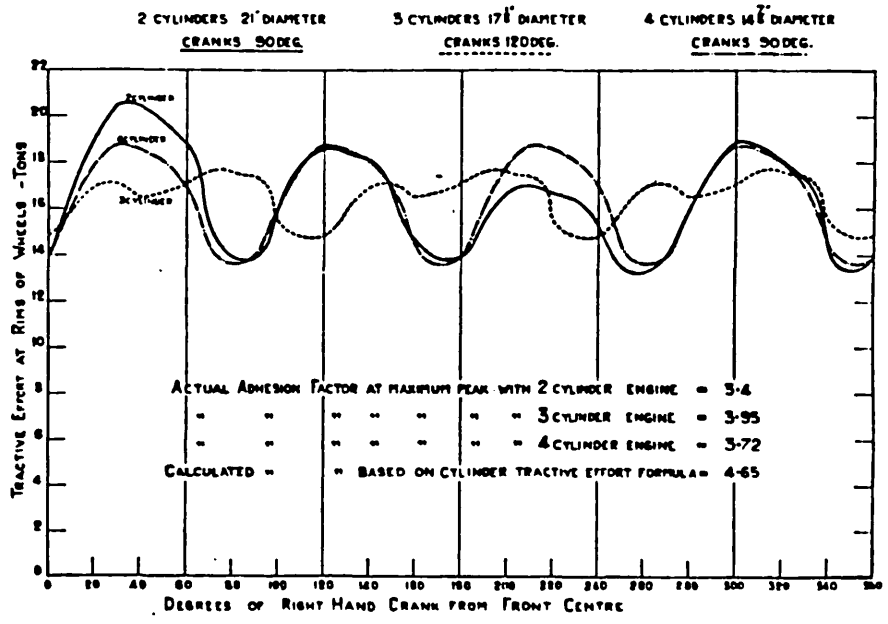

2 CYLINDERS 21" DIAMETER
CRANKS 90 DEG.
3 CYLINDERS 17½" DIAMETER
CRANKS 120 DEG.
4 CYLINDERS 16½" DIAMETER
CRANKS 90 DEG.
TRACTIVE EFFORT AT RIMS OF WHEELS - TONS
ACTUAL ADHESION FACTOR AT MAXIMUM PEAK WITH 2 CYLINDER ENGINE = 3·4
" " " " " " 3 CYLINDER ENGINE = 3·95
" " " " " " 4 CYLINDER ENGINE = 3·72
CALCULATED " " BASED ON CYLINDER TRACTIVE EFFORT FORMULA = 4·65
DEGREES OF RIGHT HAND CRANK FROM FRONT CENTRE

Fig.5.5 Variation of tractive effort for 2-, 3- and 4-cylinder engines

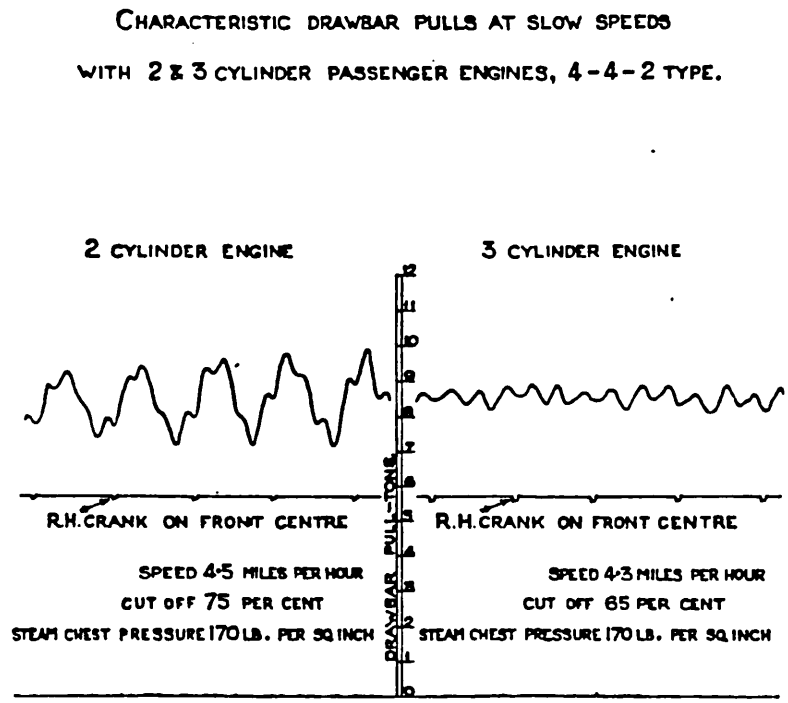

CHARACTERISTIC DRAWBAR PULLS AT SLOW SPEEDS
WITH 2 & 3 CYLINDER PASSENGER ENGINES, 4-4-2 TYPE.
2 CYLINDER ENGINE
3 CYLINDER ENGINE
DRAWBAR PULL-TONS
R.H.CRANK ON FRONT CENTRE
R.H.CRANK ON FRONT CENTRE
SPEED 4·5 MILES PER HOUR
CUT OFF 75 PER CENT
STEAM CHEST PRESSURE 170 LB. PER SQ INCH
SPEED 4·3 MILES PER HOUR
CUT OFF 65 PER CENT
STEAM CHEST PRESSURE 170 LB. PER SQ INCH

Fig.5.6 Characteristic Drawbar pulls at slow speeds with 2- and 3-cylinder passenger engines

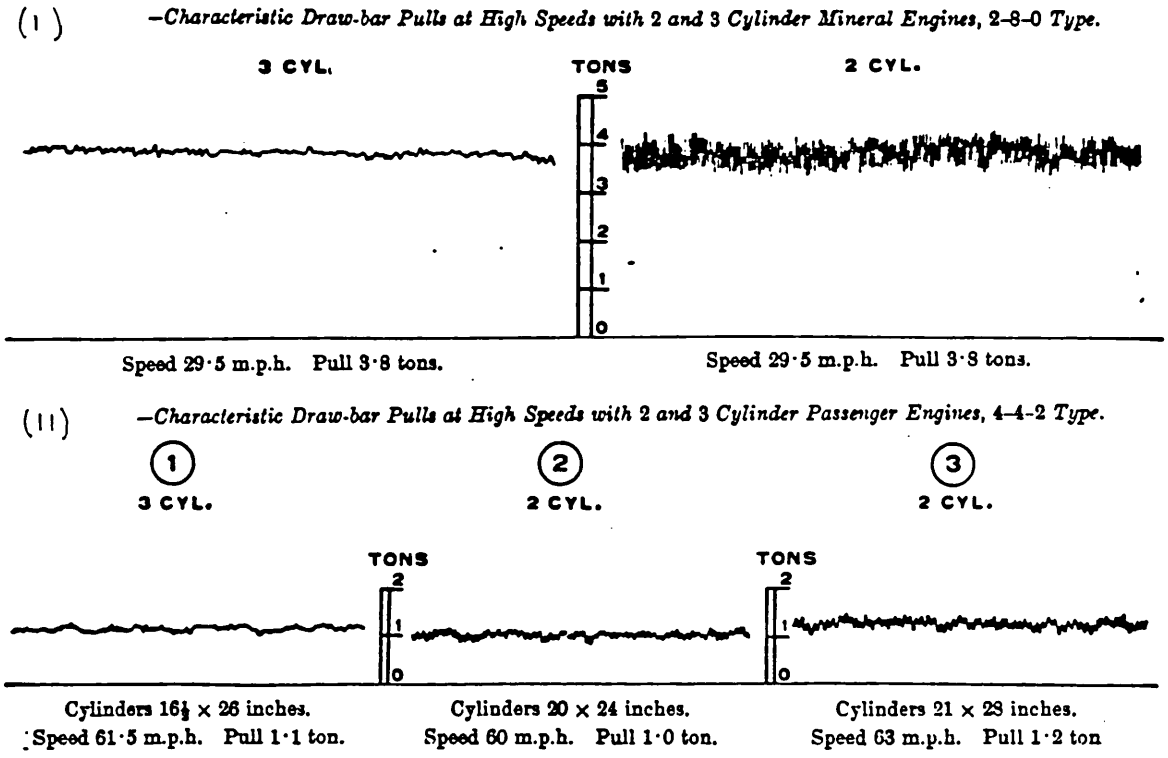

(I) —Characteristic Draw-bar Pulls at High Speeds with 2 and 3 Cylinder Mineral Engines, 2-8-0 Type.
3 CYL.
TONS
2 CYL.
Speed 29·5 m.p.h. Pull 3·8 tons.
Speed 29·5 m.p.h. Pull 3·8 tons.
(II) —Characteristic Draw-bar Pulls at High Speeds with 2 and 3 Cylinder Passenger Engines, 4-4-2 Type.
1
3 CYL.
2
2 CYL.
3
2 CYL.
TONS
TONS
Cylinders 16½ x 26 inches.
Speed 61·5 m.p.h. Pull 1·1 ton.
Cylinders 20 x 24 inches.
Speed 60 m.p.h. Pull 1·0 ton.
Cylinders 21 x 28 inches.
Speed 63 m.p.h. Pull 1·2 ton

Fig.5.7 Characteristic Drawbar pulls at high speeds with 2- and 3-cylinder mineral engines

Commenting upon these he states

The three-cylinder locomotive has proved itself to be very steady running at high speeds; in this respect it is superior to two-cylinder engines, but probably not as good as the four-cylinder type. The effect of the revolving parts can, of course, be neutralized by other revolving weights, but the reciprocating parts can only be properly balanced by other reciprocating weights moving in a directly opposite direction; this is impracticable, and therefore a portion of the reciprocating masses is balanced by revolving weights. This decreases the disturbance in the horizontal plane, but introduces one in a vertical direction, due to the centrifugal action of the excess counterbalance. This vertical disturbance is usually referred to as "hammer-blow", and if large, has a bad effect on the track and bridges, so to keep it within safe limits, it is only possible to balance a proportion of the reciprocating parts. The usual practice in this country is to balance from half to two-thirds of them.

With the three-cylinder arrangement the parts are lighter per cylinder, so the weight of the excess counterbalance can be reduced. Further, owing to the equal spacing of the cranks, it is not necessary to balance the same proportion, so the excess counter-balance can be still further reduced.

Another advantage is that the phase difference

> of the balance weights on the opposite sides of the engine is much greater than in the case of the two-cylinder engine, the resultant of the two forces being much smaller on this account.[26]

A little further on, referring to Fig.5.7(ii) he comments

> The nature of the pull curve is about the same for all engines, but the three-cylinder engine has a great advantage over the two-cylinder ones, inasmuch that it gives as regular a pull with practically no hammer-blow.[27]

These remarks, taken together, give a comprehensive view of this eminent designer's thoughts on the subject of balancing three-cylinder locomotives and their advantages in this respect compared with two-cylinder engines. But it is also revealing in a number of other ways and not least by the fact that in the mid-1920s the speaker should have deemed it not inappropriate, even with an audience composed almost entirely of professional mechanical engineers, to detail the conditions of rotary and reciprocating balance. Similarly, his assertion that the balance of reciprocating parts by other reciprocating parts moving in opposite directions was impracticable was manifestly false, belied by historical evidence, and could only be regarded as relevant in the somewhat arbitrary, self-imposed, commitment to a complete and utter disregard of the possibility of using

four-cylinder locomotives. A significant merit of the four-cylinder arrangement was precisely its facility for balancing the reciprocating parts amongst themselves without the need of revolving balance weights in the driving wheels. Early in the century it had been stated in the Institution that there were over 2,000 such engines in use on the Continent and in his own country the G.W.R. had been operating them for about twenty years, facts of which Gresley could not have been ignorant, and therefore on this argument his position was not tenable.

Summarising the advantages of the three-cylinder locomotive he stated that it permitted a reduction in the hammer-blow which, of course, was true but it is equally true that the four-cylinder arrangement allowed the hammer-blow to be eliminated entirely - a fact which he omitted to mention.

In looking at this piece of evidence, however, it is important to set it within the context not only of the general and urgent problem of the dynamic relationship between locomotive and track but also in the sphere of Gresley's own experience and view of the locomotive world. Undoubtedly, his standing and authority as a competent designer was established in 1922 with his 'A1' class locomotives which soon earned the reputation of 'steady runners' at high speeds. They fulfilled requirements and he must have been satisfied with a very successful design. (The success of this design may be judged from the fact that A.H. Peppercorn's 'Pacifics' - the last express engines to be designed and built by a British railway company were its direct descendants.)

For further enlightenment his design philosophy must be

taken into account. Since greater power could not be secured within existing parameters of locomotive boilers (steam raising capacity and steam pressures) and the restrictions of loading gauges it could only be obtained by increasing the number of cylinders. It is appropriate here to quote the man himself.

> A three-cylinder engine is a cheaper engine to build and maintain than one with four cylinders, and moreover possesses certain characteristics in which it is superior. It will meet the requirements of the near future for increased power which, owing to physical limitations, cannot be met by the two-cylinder arrangement.
>
> Undoubtedly a four-cylinder engine can be designed, the power of which will exceed that of a three-cylinder within the same gauge limits, but the construction of such an engine at the present moment would be premature...'[28]

Since he had no significant experience with four-cylinder engines his comment on the comparative cost of maintenance was presumably surmise. In the course of his paper he had claimed that greater mileage between general repairs was attained with three-cylinder locomotives compared with two-cylinder machines, a practical advantage which he attributed principally to lower stresses in the motion parts and the better balancing obtainable. With equal validity this line of argument could be extended to four-cylinder engines because the same

principles would apply with even greater force - as indeed they had been advocated by the exponents of four-cylinder propulsion from the beginning. Although conceding that the initial cost was'a little more' M. Edouard Sauvage had claimed that the cost of maintenance did not appear greater with four than with two-cylinder engines.

The large number of variables involved, and the different methods of making assessments employed by different railway companies make an objective analysis of the innumerable claims and counter-claims seemingly impossible. An investigation of this topic might be worthwhile but it would necessarily have to be a separate study.

6. General Conditions

Reference has already been made to the situation on the G.W.R. where the balancing arrangements were such that the axle hammer-blow from the four-cylinder 'Star' class exceeded that of the two-cylinder 'Saint' class, clear evidence that sufficient consideration had not been given to the subject by those concerned. This phenomenon was not peculiar to the G.W.R. and balancing practice varied to a marked degree not only between the companies but within themselves. Available evidence leads to the inevitable conclusions that the whole topic was treated in a haphazard and inconsistent manner by the locomotive engineers on one hand and that there was little real cooperation between the mechanical and the civil engineers on the other hand. The first point is graphically illustrated by the Report of the Bridge Stress Committee which revealed,

> An examination of the data collected with regard to the balancing of locomotives in the country shows that even two-cylinder engines differ widely in this respect, some exerting far more hammer-blow than others.[29]

Bearing in mind the fact that the two-cylinder machine had been the norm throughout the nineteenth century and even during the present century remained by far the most numerous type of locomotive, it is clear from this statement that no consensus of opinion on the subject, nor uniformity of practice, had been established.

Examples of the effects of various methods of balancing are revealed by the hammer-blow figures for three 4-4-0 locomotives of the early twentieth century, given in the following table.[30]

Company	Class	Speed at 6 rps	Max. axle load	Hammer blow at 6 rps		Max. combined load at 6 rps
				Whole engine	Axle	
		mph	tons	tons	tons	tons
LNWR	George V	87	19.15	9.7	14.1	33.2
MR	2P	90	17.5	11.1	11.8	29.3
GWR	County	86	19.4	16.6	8.5	27.9

Fig.5.8 Hammer-blow at 6 rps

When considering the LNWR 'George V' Class, Fig.5.9, a two-cylinder locomotive in which the entire balance for the reciprocating parts was concentrated on the driving axle with the result that at 6 rps the hammer-blow increased the static axle load by 73.6 per cent and contrast this with the same

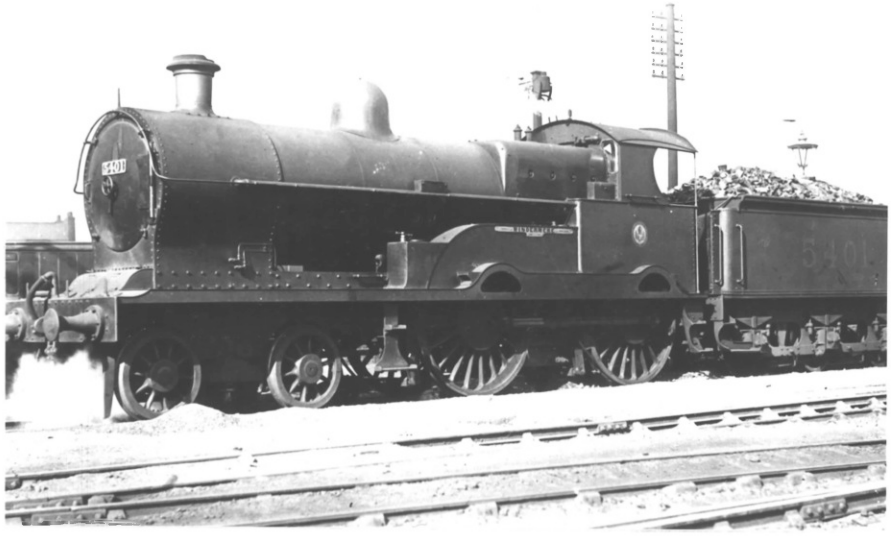


Fig.5.9 LNWR 'George V' Class, 2-cylinder locomotive

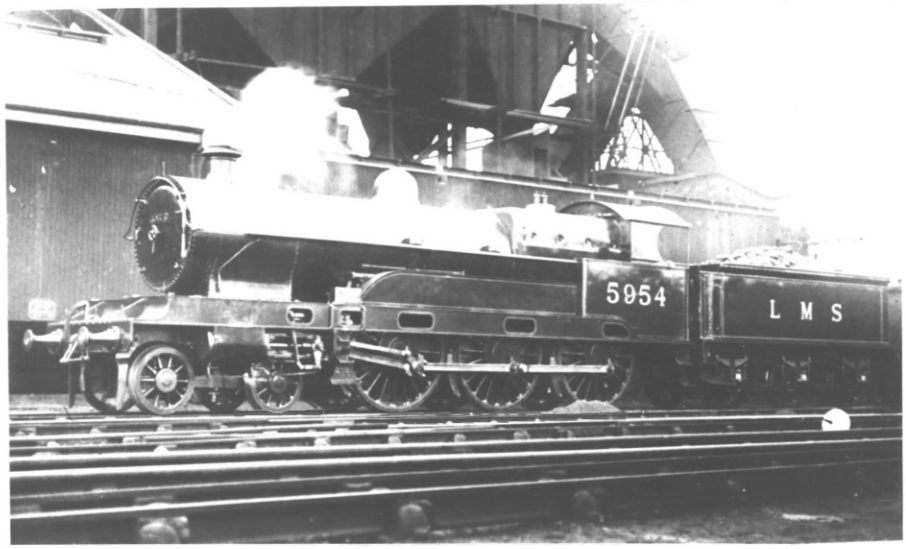


Fig.5.10 LNWR 'Claughton' Class, 4-cylinder locomotive

company's 'Claughton' class, Fig.5.10, four-cylinder engine, mentioned earlier, with no hammer-blow at the same wheel speed, it is not unreasonable to question what detailed knowledge Bowen Cooke and his staff had of the subject.

Apparently with the 'George V', so far as balancing was concerned, he merely followed established LNWR practice. When it came to planning the much bigger main-line express passenger locomotive it seems reasonable to conclude that, alerted by developments in the Netherlands he was directed to an arrangement used by F.W. Webb, in the two four-cylinder 4-4-0 engines built at Crewe in 1897. One of these was a simple-expansion locomotive, referred to in section 2 of this chapter, and the other a 'compound' but both had the same cylinder layout, that is, all in line with the two inside cylinders located beneath the smokebox, and driving the leading coupled axles. The excellent balancing characteristics of this arrangement, if noted by Webb and his colleagues were not paramount in their priorities because, as noted earlier, within months the locomotive was converted to compound working. That is, its balance was deliberately worsened by the disturbing effects introduced by the difference in piston sizes in the compound version. On the basis of Webb's one brief experiment, Bowen Cooke can hardly be regarded as following a tradition although, it must be acknowledged that, as a former pupil of Webb, he was probably aware of the arrangement. An equally significant factor was that Cooke, who had received some of his technical education in Germany, throughout his career retained a keen interest in Continental railway engineering. He must have

been well acquainted with circumstances in Holland where civil engineers allowed bigger and heavier locomotives provided that they had four cylinders all driving on to one axle. Locomotives conforming to this specification were supplied to the Dutch State Railways by Beyer, Peacock & Co., in 1910 with repeat orders following in 1911, 1912 and 1913.[31] Knowledge of events elsewhere, then, and it must be emphasised that it was on the Continent that the necessary investigations had been conducted, enabled Cooke, probably without any thorough dynamical analysis, to put a well-balanced, powerful and steady-running locomotive, the 'Sir Gilbert Claughton' on the rails in 1913. In Holland the achievement was the result of informed cooperation between civil engineers and the locomotive designers while on the LNWR Cooke's success was in spite of the hindrance of the civil engineer.

Dead weight on the axles was the criterion of the civil engineer and in a number of cases, probably indicative of the general situation, there does not seem to have been any appreciation of the significance of dynamic augment. On the insistence of E.F.C. Trench, the civil engineer, Bowen Cooke, had to reduce the size of the boiler on the 'Claughton' design to lighten the weight to produce an acceptable axle weight. Perhaps Trench could not believe that a locomotive could be without hammer-blow, but on the LNWR he permitted the 'George V' class, with a total weight in working order of 59 tons 17 cwt., which produced a maximum axle hammer-blow of 14.1 tons while for the 'Claughtons' the corresponding figures were 77 tons 15 cwt. and nil hammer-blow. The maximum static axle loads were 19.15

tons and 19.75 tons respectively. Thus we find the anomalous situation where the larger locomotive produced a maximum combined load, at 6 rps of only 19.75 tons whereas the smaller engine gave 33.2 tons!

Similarly on the Highland Railway where in 1915 F.G. Smith's 'River' class locomotives, Fig.5.11, designed and ordered, according to O.S. Nock,[32] without consulting the Civil Engineer were considered too heavy by the latter and he prohibited their use. More recently the episode of these locomotives has been the subject of an article[33] which suggests that there had originally been communication between Smith and A. Newlands, the civil engineer, on them and that the latter had accepted the original estimated weights. According to C.P. Atkins it is probable that Newlands was not advised of the revised weight of the engine. The accuracy of the details of this affair, although once more highlighting the difficulties of the historian because of the destruction of records, are not particularly important so far as the implications for this study are concerned. What is indisputable is the lack of close cooperation between the two engineers in matters affecting them jointly and Newland's preoccupation with dead weight to the exclusion of any serious analysis of dynamic effects. Smith had seemingly given proper thought to the matter and produced a locomotive with a small hammer-blow.[34] But this was not appreciated by Newlands. Smith was effectively sacked, his locomotives, of which it has been written,

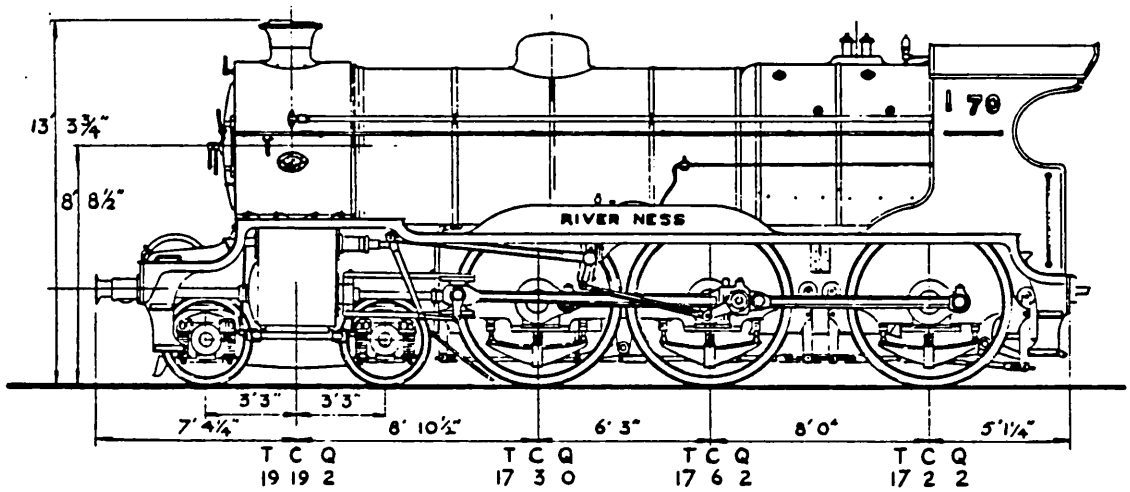


Fig.5.11 F.G. Smith's 'River' Class Locomotive, Highland Railway, 1915

> Without a doubt they were the most advanced 4-6-0s to be built for any British railway other than the Great Western prior to 1923[35]

were sold to the Caledonian Railway (at a handsome profit) and yet the 'Clan' class locomotives which were accepted by Newlands in place of the 'Rivers' were, in respect of the hammer-blow per axle, for the whole engine, and in terms of the maximum combined load at 6 rps, worse than the rejected engines as the following figures[36] show:

Class	Speed at 6 rps	Max. axle load	Hammer blow at 6 rps		Max. combined load at 6 rps
			Whole engine	Axle	
	mph	tons	tons	tons	tons
River	77	17.75	1.7	4.2	21.4
Clan	77	15.33	15.3	7.1	22.4

Fig.5.12 Hammer-blow at 6 rps of the Highland Railway 'River' and 'Clan' Class Locomotives

Comparable situations existed elsewhere. On the Great Western Railway, for example, minimal communication between the mechanical and civil engineering departments resulted in an incredible divergence of practice between them. Locomotive design continued on the basis of a maximum permissible axle load of 19.5 tons for over twenty-two years after the civil engineers had been allowing 22 tons for this parameter. And even then the inconsistency only came to light through an informal conversation between Sir Aubrey Brocklebank, a director of the GWR, Sir Felix Pole, the Company's General Manager, and C.B. Collett, the Chief Mechanical Engineer. Details of this episode are given in the memoirs[37] of Sir Felix Pole, which also provide an account of the organisation and management of the company. His astonishment on making this discovery reveals yet another factor in the deterioration of the train-on-track relationship; that is, the lack of effective management in securing the necessary coordination between the appropriate groups. Here, in one of the most prominent - and generally regarded as the most progressive - railway companies the two major engineering departments were manifestly working in isolation while the management, in some crucially important matters, were obviously unaware of what either department was doing. Such criticism was indeed envisaged by Pole himself when he cogently summarised the state of affairs,

> A critic of railway management may well comment on the fact that neither the General Manager nor the Chief Mechanical Engineer knew that for twenty-two years

> bridges were being designed to enable heavier loads to be conveyed. This, however, was quite in keeping with the highly departmentalized position of affairs that existed at Paddington for so many years....the Chief Engineer submitted his proposals to the Engineering Committee of directors without reference to the General Manager, and there is little doubt that the then General Manager and Superintendent of the Line were not even aware of what the directors had authorized as the basis of future engineering practice....Also, we may well moralize on the length of time that might still have elapsed before the extra expenditure on bridge construction would have become remunerative but for Sir Aubrey Brocklebank's inquiring mind.

Although in this particular case bridges were being over-designed, with the tendency to suppress the effects of badly balanced engines, technically and economically the procedure was inefficient and not conducive to successful railway operation. Inadmissible though it may be to generalise on the basis of what pertained on the Great Western Railway it is not unreasonable to suppose that conditions on other railways were much the same. Such a supposition is corroborated by the investigations of the Ministry of Transport after the War of 1914-1918 and which are discussed in the next chapter.

Incidents such as these indicate quite clearly how, in the absence of proper cooperation between the departments concerned, the deleterious effects of locomotives on the

permanent way and underline bridges were bound to become accentuated as locomotives increased in weight and civil engineers judged their acceptability simply on dead weight on the axle. During the period under consideration the evidence suggests that civil engineers, and probably many of the locomotive engineers too, had no real appreciation of the significance of the dynamic forces involved. The fact that a locomotive could be banned or be modified at their insistance while they allowed the running of more harmful machines leads to the conclusion that, rather than analyse the effect of a new design on the track and the bridges, they made a summary decision on a rule-of-thumb basis of static axle weight. The reaction of say, E.F.C. Trench, the civil engineer who compelled C. Bowen Cooke to lighten the 'Claughton' and who subsequently became a member of the Bridge Stress Committee, to the Report's revelation that these locomotives had no hammer-blow whatever is an interesting matter for speculation. A red face, perhaps! This point cannot meaningfully be pursued further. A major problem for the historian of technology is that engineers, in general, do not produce written records describing their work. If they lack the time and inclination to chronicle their successes it can hardly be expected that failures will be enumerated.

In the absence of evidence to the contrary one can only conclude that these men, within their professional milieu, were acting in a competent and conscientious manner. They made their decisions on the empirically derived rules-of-thumb that were the contemporary relevant standards; the need for a more

analytical, scientific treatment had not yet emerged although its appearance was not far in the future. Meanwhile, the authority of the civil engineer was supreme and, apparently, seldom challenged and even more rarely successfully so. For example, Cox cites the case of a 4-6-4 Baltic Tank engine designed by George Hughes, of which ten were built at Horwich in 1924, where the design proposals were rejected eight times before acceptance was granted.[39] He also relates how Stanier, in submitting proposals for a two-cylinder 2-6-0 received in reply twenty-one pages of running restrictions, because the width over the cylinders was thought to be too great.[40] But, unlike his predecessors, instead of accepting this Stanier demanded proof and after a 'negligible amount of setting back of platform coping stones at a few stations', the universal use of outside cylinder locomotives on the system became possible.

Reference has already been made, concerning C.J. Bowen Cooke, to the knowledge of balancing possessed by the locomotive engineers themselves and by their staffs. This engineer was responsible for both the 'George V' class and the 'Claughton' class in which the achievement in balance ranged from the appallingly bad to the exceedingly good and this remarkable contrast leads to the question of who was actually responsible for the balancing of the locomotives. Ultimately, of course, it was the Chief Mechanical Engineer but in practice the task seems to have devolved upon the anonymous drawing office staff or exceptionally upon one of the CME's assistants. Probably not untypical of events elsewhere, H.A.V. Bulleid, in his biography of his father, describes the latter's experience during the

mid-1920s as Gresley's assistant in the matter of balancing the three-cylinder Class K3 2-6-0 locomotive. Bulleid received the order, 'Get the balancing worked out, the Drawing Office don't know how to do it properly.'[41]

And the biographer tellingly continues, ' Nor did Bulleid know how to do it, but he acquired and studied the recently published paper on balancing by Professor Dalby and saw to it that it was correctly applied by the Drawing Office.' Subsequently the calculations were checked and confirmed by Professor Dalby. Amusingly he concludes this little anecdote by quoting his chuckling, satisfied father, 'H.N.G. never thought of asking me where I got my information'.

These events occurred after the return of Oliver Bulleid to Doncaster in March 1919 and presumably the 'recently published paper' refers to Dalby's 'The Balancing of Locomotives',[42] his only 'paper' on the subject - but that was given to the Institution in 1901 and could hardly be regarded as 'recent'. Additionally, the five examples with which the paper was illustrated were all confined to two-cylinder engines and its usefulness must have been in terms of giving the general method which Bulleid then applied to the three-cylinder engine. This in itself suggests that Dalby, at the time, felt that the two-cylinder locomotive was the only type of practical significance. Replying to an observation that his paper had not illustrated the case of a three-cylinder locomotive he stated that he would have liked to have included one but the absence of data and the desire not to lengthen the paper had prevented him from doing so. Subsequent events lead to the conclusion that

this was a polite impromptu answer and in reality he did not deem multi-cylinder locomotives important enough to warrant treatment. With considerably more space at his disposal he chose not to give examples of three- or four-cylinder locomotives in the first three editions of his book on the subject which appeared in 1902, 1906 and 1917 respectively. They were accorded space only in the fourth and final edition of the work published in 1929, that is, after the advantages of these types for heavy, powerful locomotives had been emphasised by the Bridge Stress Committee.

It is also possible that Bulleid was led, by the discussion on the paper[43] in the Proceedings of the Institution of Mechanical Engineers, to a specific treatment of the three-cylinder machine in the pages of Engineering.

The accuracy of the scanty details related by Bulleid's son, especially identification of the actual document consulted by his father, are obviously open to question. Nevertheless, the episode is not without its message insofar as it shows that not only was the necessary knowledge lacking in those who should have possessed it but even an awareness of how to obtain it was absent.

Three-cylinder locomotives had been used on the neighbouring NER since 1911 and Gresley himself had built one in 1918 and so his own Drawing Office had obviously contended with the problem, even if not to his satisfaction. In these circumstances, bearing in mind the growing importance of multi-cylinder propulsion and the likely recurrence of the task, it might have been expected that Gresley would have instructed

his staff on the correct procedure or at least have provided them with some reliable information from which they could have informed themselves of the proper method but, apparently, he did neither. Instead, without ascertaining whether he was capable of undertaking the job, he merely handed it over to his assistant. Unquestionably balancing practice was largely a matter of convention, persisting beyond the Grouping, and giving variable results ranging from satisfactory to poor with the distinction hardly recognised and not acknowledged. This situation is not peculiar to balancing and has a parallel in the application of long travel piston valves to high degree superheated locomotives by the Lancashire and Yorkshire Railway in 1908.

> ...the arrangement which in combination produced the modern steam locomotive in its final form. It did not however develop or even recognise the treasure it had found.[44]

Difficulties with the lubrication of these piston valves caused their replacement with short travel valve gear even at the expense of a marked drop in engine performance. Indeed piston valve lubrication and other tribological problems, like those of balancing, confronted the locomotive engineer until the end of steam traction. In the case just cited, of course, there is a distinction to be made in the comparison with the problem of balancing. The choice of reverting to short travel valves with the consequent inferior performance of the machine was

consciously made by the locomotive engineers in the light of their own experience and is merely an example of the compromise nature of engineering. Less efficient steam utilisation was accepted as a worthwhile exchange for an amelioration of the lubrication problem. Success, however, was not essentially dependent upon understanding but upon the results of observation and experience sensibly applied. A striking example of this, which I have discussed elsewhere,[45] was the axle-box designed by W. Bridges Adams and used for over thirty years before the discovery of hydrodynamic lubrication by Beauchamp Tower in the early 1880s.

In the case of balancing the situation was different insofar as the poor performance in this respect, due to inadequate understanding, was within neither the purview nor the responsibility of the mechanical engineer. He would, of course, have been aware of the failures and inevitable wear and deterioration of his machines, these processes being accentuated by the unnecessarily high stresses induced by improper balancing, but this cause did not manifest itself in isolation and thus attract his attention. Eventually his notice was forcefully drawn to the matter by the increasing concern of the civil engineers and in particular those charged with the provision and maintenance of bridges. This is the subject of the next chapter.

Before passing to this, however, it is worth recalling that the possibility of achieving a much better standard of balancing with three- and four-cylinder locomotives existed during this period. The necessary information had been

published. Although, as mentioned earlier, Professor Dalby's paper of 1901 did not give illustrative examples of multi-cylinder locomotives it briefly stated the conditions under which, with a four-cylinder engine, both variation of tractive force exerted by the engine and variation of rail pressure could be avoided. C.E. Wolff's Modern Locomotive Practice,[46] published in 1904, gave a somewhat lengthier but general consideration of three- and four-cylinder engines and E.L. Ahrons' paper[47] to the Institution of Locomotive Engineers in 1914 made particular reference to these types.

This comprehensive paper, stimulated by the growing numbers of three- and four-cylinder locomotives and using Professor Dalby's method, illustrated in detail the balancing of British engines with two, three and four cylinders. In a separate section special consideration was given to the question of determining the proportion of reciprocating masses to be balanced. Ahrons was of the opinion that '...in this country with modern heavy engines too great a proportion of the reciprocating masses is balanced.'[48] It was a clarion call that went unheeded for many years and even in the final stages of steam traction the matter was never resolved completely.

To those who would listen the ideal of perfection had been proclaimed. In the penultimate paragraph of his paper Dalby had unequivocally issued the challenge,

> ...it is possible to construct a locomotive in complete balance (neglecting the obliquity of the connecting rod) without the addition of balance-weights of any kind, by

> properly proportioning the masses and crank angles, but whether such an engine would be satisfactory in all of the many other exacting conditions it has to fulfil is a matter which can only be decided by experiment.[49]

His pragmatic qualification acknowledged the compromise nature of the locomotive designer's task. An appreciation of this may be gained from a study of 'Locomotives Designed and Built at Horwich, With Some Results'.[50] Rarely do we find a Chief Mechanical Engineer giving explicit details of his design decision but here, faced with the need to provide a powerful locomotive capable of rapid acceleration the four-cylinder arrangement was chosen because of its '...many advantages from a mechanical standpoint, such as division of stresses and superior balancing'.[51]

The balancing could have been most successfully achieved by all four cylinders driving on to one axle but a divided drive was adopted because Hughes commented 'Four cylinders, of a necessity, bring about steam and exhaust pipe complications'[52]. and his solution to the problem was an arrangement where

> The inside cylinders drive on the first axle, and a reasonable length of connecting-rod results. The oustide cylinders are fixed behind the inside, and about midway between the bogie wheels; these drive on to the second axle. By this disposition the steam and exhaust pipes can be kept within the smoke-box, thus minimizing the additional condensation brought about by exposed

> steam-pipes, and also obviating the increased back-pressure which necessarily follows when the exhaust has to be led through long and tortuous passages.[53]

Hughes also considered the ideal of 'perfect balancing' and it is interesting to have the thoughts of a practising engineer on this possibility. They are, in effect, an answer to Dalby and the reason why this degree of perfection was never sought in this country.

> Absolutely perfect balancing could have been achieved without the aid of balance weights, if the angles of the cranks, the disposition of the cylinders, and the weights of the reciprocating parts had been arranged to neutralize amongst themselves the reciprocating disturbing forces; and then by balancing the revolving masses, the variations of rail load, and horizontal swaying couple, would have disappeared. The engine would have then been perfectly balanced, except for a slight vertical component produced by the obliquity of the connecting rod. This arrangement, known as the Yarrow-Schlick-Tweedy system,[54] introduces complications from the fact that the disposition of the cranks involves the use of an independent set of valve-gear for each cylinder. All these refinements are extremely costly, and the author came to the conclusion that the compromise arrived at was not only sound commercially,

but as near scientific perfection as common sense dictated.[55]

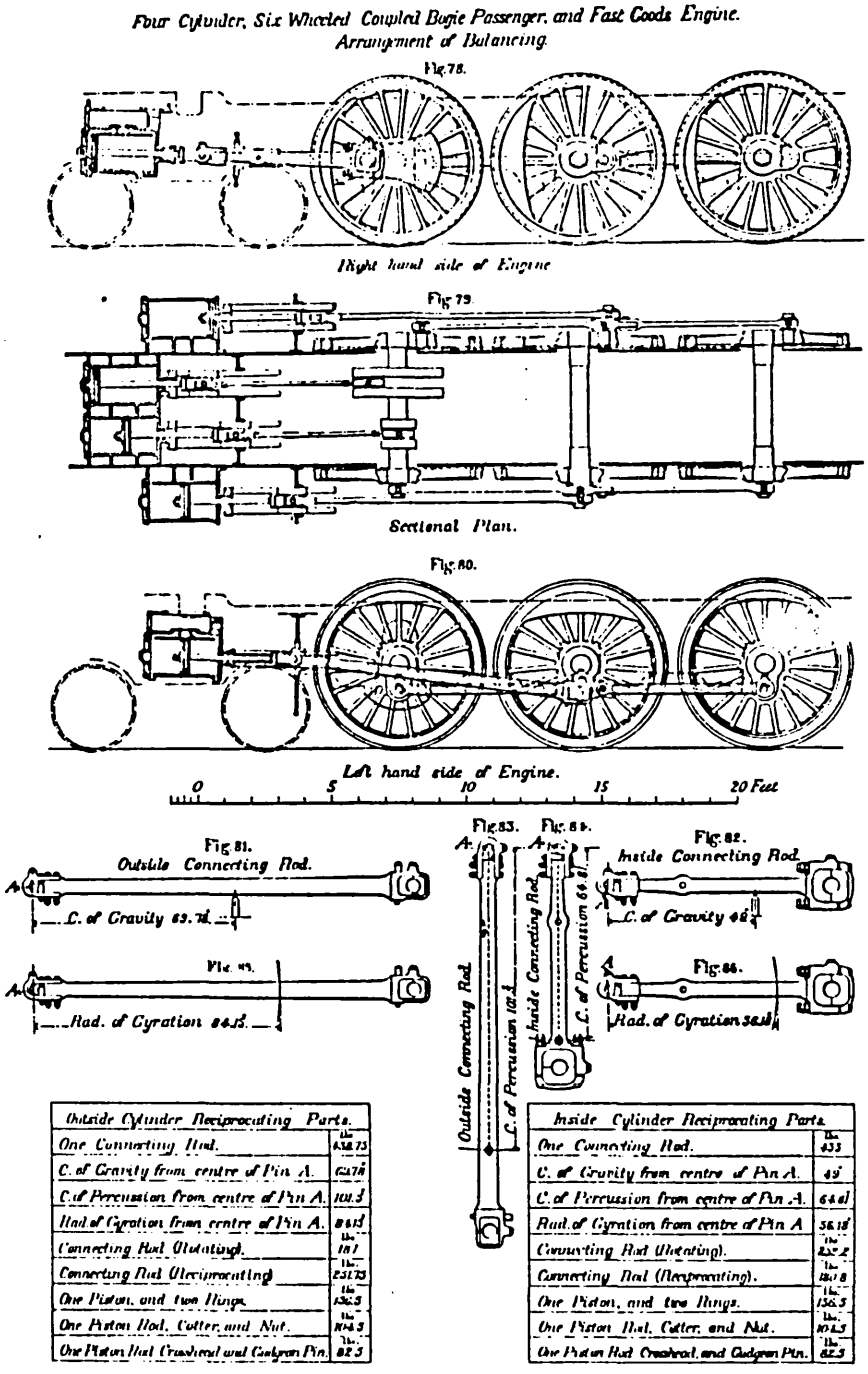

Four Cylinder, Six Wheeled Coupled Bogie Passenger, and Fast Goods Engine.
Arrangement of Balancing.
Fig.78.
Right hand side of Engine.
Fig.79.
Sectional Plan.
Fig.80.
Left hand side of Engine.
0
5
10
15
20 Feet
Fig.81.
Outside Connecting Rod.
C. of Gravity 69.7d.
Rad. of Gyration 84.5.
Fig.83.
Fig.84.
Fig.82.
Inside Connecting Rod.
C. of Gravity 46
Fig.86.
Rad. of Gyration 36.8
Outside Connecting Rod.
C. of Percussion 101.3
Inside Connecting Rod.
C. of Percussion 64.81
Outside Cylinder Reciprocating Parts.
One Connecting Rod. lbs. 458.75
C. of Gravity from centre of Pin A. 69.76
C. of Percussion from centre of Pin A. 101.3
Rad. of Gyration from centre of Pin A. 84.5
Connecting Rod (Rotating). lbs. 181
Connecting Rod (Reciprocating) lbs. 251.75
One Piston, and two Rings. lbs. 136.5
One Piston Rod, Cotter, and Nut. lbs. 114.5
One Piston Rod Crosshead and Gudgeon Pin. lbs. 82.5
Inside Cylinder Reciprocating Parts.
One Connecting Rod. lbs. 433
C. of Gravity from centre of Pin A. 46
C. of Percussion from centre of Pin A. 64.81
Rad. of Gyration from centre of Pin A 36.18
Connecting Rod (Rotating). lbs. 332.2
Connecting Rod (Reciprocating). lbs. 181.8
One Piston, and two Rings. lbs. 136.5
One Piston Rod, Cotter, and Nut. lbs. 114.5
One Piston Rod Crosshead, and Gudgeon Pin. lbs. 82.5

Fig.5.13 Balancing arrangements for George Hughes' 4-cylinder locomotive

According to Hughes he gave this system some thought when considering the question of balancing but he admitted that perfection in the design of the engine had been sacrificed to obtain simplicity and to conform to existing workshop procedures. Nevertheless, his balancing arrangements which, unusually, were depicted in detail in his paper, Fig.5.13,[56] 'resulted in making this engine a very steady and smooth-running machine'. He had obviously given the subject the attention it merited and clearly saw the possibility of increasing the axle-load by the diminution or elimination of the hammer-blow. The appearance of his paper in the early days of four-cylinder locomotives and just before the entry, on a significant scale, of three-cylinder engines focused attention on this important topic. It emphasised the design opportunities afforded by good practice and highlighted the dire consequences of neglect of the issue. But the message went unnoticed or largely unheeded.

As this chapter has shown the story of balancing during this period is one of inconsistency with the level of achievement ranging from the appallingly bad to virtual perfection and precious little evidence to suggest that the majority of those involved and responsible for this state of affairs could distinguish between the two states.

Nor was this unfulfilled state of affairs confined to the dynamics of locomotives alone; it was paralleled by other aspects too. Of this period it has been written

> Few locomotives came near the potential output because the huge boilers, large cylinders and rising pressures were negated first by inadequate valves, motion and draughting, and secondly by serious leakage of superheated steam past the piston valves.[57]

The opportunity to optimise design potentials was missed and not until the work of the Bridge Stress Committee was undertaken in the 1920s was the variation in balancing procedures revealed, the importance of the subject forced upon the attention of locomotive engineers, the significance of dynamic augment as opposed to static axle loads put into context for civil engineers, and the way cleared for a more rational treatment of both balancing problems and bridge design.

References and Notes

1. Mitchell, B.R. and Deane, Phyllis, Abstract of British Historical Statistics, Cambridge University Press, 1962, p.226. The accuracy of this statistical information is diminished to the extent that the figures quoted for the numbers of passengers carried do not include the holders of season tickets. Similar figures quoted by J. Simmons in The Railway in England and Wales 1830-1914, Vol.1, p.276, give an incremental factor of 2.66.
Over the same period, according to Mitchell and Deane, freight traffic growth is represented by a factor of 2.38.

2. Montagu, George, Ten Years of Locomotive Progress, Alston Rivers Ltd., London, 1907, p.1.

3. Stretton, Clement E., The Locomotive Engine and its Development, Crosby Lockwood and Son, London, 1903, Sixth edition, Preface, p.vi.

4. Reed, Brian, 150 Years of British Steam Locomotives, David & Charles, Newton Abbot, 1975, p.85.

5. Engineering, 16 November 1866, p.369.

6. Ahrons, E.L., The British Steam Railway Locomotive 1825-1925, The Locomotive Publishing Company Ltd., London, 1927, p.301.

7. Without reference or qualification, Ahrons' (as ref.6), asserts that Manson's main objective was to produce a

better balanced engine but, as noted, Manson did not repeat the design. Nevertheless, it is reasonable to conclude that its performance was satisfactory because when, after a quarter of a century's service, the locomotive was completely rebuilt by R.H. Whitelegg, in 1923, it was reconstructed as a four-cylinder engine, albeit with slightly different cylinder sizes.

8. Ahrons, op.cit., p.301.

9. Skeat, W.O., 'The Decapod Locomotive of the Great Eastern Railway', Transactions of the Newcomen Society, Vol.XXVIII, 1951-52 and 1952-53, p.169.

10. Holden, J. and Russell, F.V., Patent No.28946, 31 December 1902.

11. Skeat, op.cit., p.170.

12. Ibid., p.183.

13. The Engineer, Vol.95, 6 February 1903, pp.135-136.

14. The Engineer, 13 February 1903, p.173.

15. Skeat, W.O., 'The Decapod Locomotive of the Great Eastern Railway: Supplementary Note', Transactions of the Newcomen Society, Vol.XXIX, 1953-1954 and 1954-1955, pp.263-264.

16. Bulleid, O.V.S., 'Locomotives I Have Known', Proceedings of the Institution of Mechanical Engineers, Vol.152, 1945, pp.343-344.

17. Sauvage, Edouard, (i) 'Recent Locomotive Practice in France', Proceedings of the Institution of Mechanical Engineers, 1900, pp.375-433; (ii) 'Compound Locomotives in France', Proceedings of the Institution of Mechanical

Engineers, 1904, pp.327-468.

18. Ahrons, op.cit., p.326.

19. Cox, E.S., Locomotive Panorama, Vol.1, Ian Allan, London, 1965, p.47.

20. Sinclair, Angus, Development of the Locomotive Engine, MIT Press Edition, 1970, p.489.

21. Sauvage, op.cit., (ii).

22. Gresley, H.N., 'The Three-Cylinder High-Pressure Locomotive', Proceedings of the Institution of Mechanical Engineers, 1925, pp.927-986.

23. Ibid. This diagram is reproduced from p.936 of the paper where it is Fig.2.

24. Ibid. This diagram is reproduced from p.940 of the paper where it is Fig.4.

25. Ibid. These diagrams are reproduced from p.942 of the paper where they are Figs.6 and 7.

26. Ibid., pp.941 and 943.

27. Ibid., p.943.

28. Ibid., p.948.

29. Department of Scientific and Industrial Research, Report of the Bridge Stress Committee, HMSO, London, 1928, p.13.

30. Nock, O.S., The British Steam Railway Locomotive 1925-1965, Ian Allan, London, 1966, p.36.

31. Hills, R.L. and Patrick, D., Beyer, Peacock Locomotive Builders to the World, The Transport Publishing Company, Glossop, 1982, p.130.

32. Nock, O.S., The Highland Railway, Ian Allan, London, 1966, p.153.

33. Atkins, C.P., 'More Light on the Highland 'Rivers' - the mystery solved?', Railway World, February 1978, pp.75-77.

34. In the absence of conclusive evidence, however, the possibility cannot be entirely excluded that the small hammer-blow was the outcome of a fortuitous choice of the magnitude of the balance masses rather than as the result of careful design.

35. Atkins, C.P., The Scottish 4-6-0 Classes, Ian Allan, London, 1976, p.26.

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37. Pole, Sir Felix J.C., Felix J.C. Pole: His Book, Town and Country Press Ltd., Bracknell, 1968, pp.87-88.

38. Ibid., pp.88-89.

39. Cox, op.cit., p.31.

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42. Dalby, W.E., 'The Balancing of Locomotives', Proceedings of the Institution of Mechanical Engineers, 1901, pp.1157-1208.

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44. Cox, op.cit., p.8.

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47. Ahrons, E.L., 'The Internal Disturbing Forces in and Balancing of Locomotives (with special reference to three- and four-cylinder Engines)', Journal of the Institution of Locomotive Engineers, Vol.IV, 1914, pp.3-78.

48. Ibid., p.35.

49. Dalby, op.cit., p.1187.

50. Hughes, George, 'Locomotives Designed and Built at Horwich, With Some Results', Proceedings of the Institution of Mechanical Engineers, 1909, Parts 3 and 4, pp.561-653.

51. Ibid., p.575.

52. Ibid., p.576.

53. Ibid., p.576.

54. A development of Yarrow's work, in which a marine engine was balanced by bob weights driven by eccentrics,

described in his paper to the Institution of Naval Architects (see Ch.4, Ref.43), led to a method, known as the Yarrow-Schlick-Tweedy system. In this, adjustment of the reciprocating masses and the crank angles, enabled balance to be achieved, in the line of stroke, of primary and secondary forces and primary couples, leaving only secondary couples unbalanced.

55. Hughes, op.cit., p.578.

56. Ibid., p.579.

57. Reed, op.cit., p.86,

Chapter 6

THE PERMANENT WAY AND THE BRIDGE STRESS COMMITTEE

1. Early Train-Track Experience

It was from the civil engineering side of railway operation that the attention of locomotive engineers was eventually drawn to the unsatisfactory state of balancing and its consequences for the permanent way and the underline bridges were made manifest. Throughout the history of steam traction there has been a conflict of requirements which led from the very beginning to a separation of the activities of the engineers involved resulting in the 'systems' nature of the enterprise being lost.

The relationship between locomotive and track however envisaged by the early pioneers, Trevithick, Blenkinsop and the Stephensons as a harmonious system was not successfully achieved for a number of reasons and recent writers who see this as an accomplishment of the nineteenth century appear to base their judgement on the ideal itself rather than on the basis of any evidence of its attainment.

The following statements are typical of this view:

> It is arguable that the locomotive engineers of the nineteenth century had more vision than the automobile engineers of the twentieth; for in the nineteenth century they conceived of the vehicle and its road as one system and designed them together.[1]

> The history of locomotives is too often thought of

> solely in terms of mechanical engineering. Their relationship to the track on which they ran is a fundamental element in their design.[2]

> The successful union of locomotive and permanent way... resulted in a system termed "Machine-Ensemble".[3]

Ideas such as these originated in the marked contrast between the railway and other transport systems and also by developments in the locomotive-track relationship but, nevertheless, excluding the dynamic interaction which came to the fore only after earlier problems had been identified and solved. Unlike both road transport and canals where individually controlled vehicles and vessels, respectively, could operate simultaneously and satisfactorily because of their manoeuvrability the railway was inflexible in the sense that the train was both guided and constrained by the track. Possibilities of 'overtaking' or 'moving over' to give way to an oncoming train did not exist. These technical aspects of the inseparability of train and track were reinforced by the economic structure of the railway as opposed to the other modes of transport. In the former case both track and locomotives operating on it were owned by the railway company whereas turnpike and canal companies owned the road or waterway while the carriages and boats using them were, in the main, separately owned.

So, too, the various stages in the transition from flat-tyred wheels on cast-iron plateways, to flanged wheels on rolled

wrought-iron, and eventually steel, edge-rails confirmed this view. The brittle and weak cast-iron soon gave way to wrought-iron which, because of its low abrasion resistance, quickly wore away and needed frequent renewal. Thus constant breakage, weakness and wear which characterised railway operation during the early years and necessitated frequent track replacement, not only established this practice as the norm in the minds of engineers and management (although they disliked the requirement), it effectively masked the track-working problem. Steel rails, with their superior wear-resisting qualities, began to appear in the 1860s and the upward trend in locomotive weights, accompanied by an increasing volume of traffic, from the 1870s brought about the situation where the track-working characteristics of locomotives unmistakably forced themselves to the attention of engineers.

Extensive fracture of the plate rails by the unsprung mass of Trevithick's Penydarren locomotive terminated its traction service; machine and its way were clearly incompatible. A conscious attempt was made by Blenkinsop to overcome the difficulty of securing adequate adhesion with plain wheels on contemporary track by employing a rack drive and his patent[4] was for a railway system rather than for an engine. Indeed it did not specify any particular prime mover although the patentee expressed his preference for the steam engine. Although not destined for widespread adoption this was a successful railway system, indeed the first measured by the criterion of commercial success.[5]

The Stockton and Darlington Railway, laid with both

Birkinshaw wrought-iron rails and cast-iron rails, was troubled by locomotive-track interaction essentially due to the the use of unsprung engines on light and weak rails, the situation being worsened by poor construction and maintenance problems. Maintenance was let out in length contracts and was not always well done. This practice was also adopted by the Liverpool and Manchester Railway (and, indeed, by other railways) but in 1837, by which time the Company had had to renew its whole line, it undertook this task itself.

It is not the purpose here to investigate the development of the track and this subject may be studied elsewhere[6] but the constant breakages indicate a failure to match the locomotive and track to each other. Thus within two years of its opening the original wrought iron 'fish-bellied' rails, fifteen feet long and weighing 35lb per yard had proved inadequate and had led the Liverpool and Manchester Railway into a series of experiments with the object of improving the rails. By the early 1840s the employment of rails weighing 70lb per yard (and sometimes more) was usual. And so, after no more than ten years, in the attempt to keep pace with the constantly growing locomotives it had been necessary to double the weight of the rails with a consequent increase in the weight of chairs to hold them and so on. In this progression the track lagged behind the locomotive, never were they in phase. There are a number of factors which account for this predicament. Most significant, of course, is the fact that engineers had no precedents to guide them and the acquisition of experience was both a function of time and of careful observation and analysis

of the operation of all the component parts of the system. The complexity and scale of the undertaking precluded the possibility of one man keeping the entire business under his personal purview. That the occupation of the Stephensons with the promotion of railway schemes prevented their involvement with the detail design of locomotives after a very short period is well-known. Likewise Brunel's appointment of Daniel Gooch as his Locomotive Superintendent in 1837 initiated and formalised the separation of responsibility for locomotives as a characteristic of railway engineering and organisation. As with the Stephenson's, Brunel devoted himself to the civil engineering side of railways. Within the separate spheres experience had to be gained, lessons learned and erroneous opinions corrected and modified. Commonly, but erroneously, the idea was held by engineers, Brunel and the Stephensons among their number, that a rigid track was essential for smooth riding although as early as 1837 W.B. Adams, by analogy with carriages on roads, had expressed the view that the track should possess 'elasticity'.[7] Experience proved him right, flexibility was necesssary. The track itself had to have a good foundation capable of sustaining the heavy track and the pounding it took from locomotives and their trains. With rail lengths of 30ft there would be 176 joint impacts per rail per mile and it was not until the 1880s that these lengths were in common use on the LSWR for example. Before 1847, when W.B. Adams and R. Richardson patented the fishplate for joining two rails together, and thereby brought about a great advance in track construction and performance, the locomotive on the rails can

hardly be regarded as a successful unison, designed together, to produce a harmonious mode of operation.

As we have seen it had been in these far from satisfactory circumstances that W. Fernihough had adopted the use of weights in the rims of locomotive driving wheels to balance the inertia forces generated by the reciprocating masses. Although he recognised that this introduced a vertical force he dismissed this from the reckoning as has been noted earlier, Chapter 3 section 1, with a bland '...(it) may be considered as nothing, because it merely acts upon the rail.' As this earlier chapter has shown although this view was not universally held and did not go unchallenged, the practice of balancing by the use of weights in wheels became general and with it the cyclic load it placed upon the rails.

Despite the occasional reference to the state of perfection of the permanent way[8] the tenor of a number of papers read before the Institution of Civil Engineers from the 1860s onwards is its failure to meet the demands of the enormous increase of traffic and the introduction of heavier engines and rolling stock.[9]

Lack of experience and failure to foresee this trend resulted frequently in little or no provision in the finances of a railway at its beginning for renewal and improvement of the track. G.P. Bidder spoke of the difficulty in obtaining the sanction of Boards of Directors for increased expenditure on the permanent way to provide better materials, for rails, sleepers and chairs.[10] In his paper on Railway Accidents J. Brunlees claimed that for high speed working some tracks were in such a

defective state that traffic could not be worked economically.[11] The use of better quality materials was seen as the main requirement by R. Price Williams while in the discussion on this paper C. Vignoles argued for a permanent way with the minimum number of components. He advocated the adoption of the flat-bottomed rail with the weight of the abandoned chairs to be added to the rails, thus obtaining a better rail at little extra cost.[12]

The discussions on these papers and indeed generally on the papers read before the professional institutions provide a valuable source of information on the views and opinions of contemporary engineers. Thus in this last paper referred to we discover Henry Bessemer suggesting that the first cost of steel rails could be reduced by diminishing the weight of the rail[13] - an unusual idea in the light of previous railway experience and fortunately one which was ignored by those in the business. More significantly for the future of railways F.W. Webb revealed to the audience that arrangements were almost complete at Crewe for the production of 350 tons of steel each week, of which 300 tons would be used for the manufacture of rails.[14]

Only slowly was the transition from wrought iron to steel rails accomplished beginning in the 1860s and not being complete for main lines until early in the present century. Far from Bessemer's idea of a reduction in rail section being possible the inexorable upward trend of locomotive weights was accompanied by an increase in rail section to a standard of 95lb per yard for most important main lines in the early years of this century.

By this time, however, in the face of experience of the permanent way engineers and more particularly of the bridge engineers the variation in wheel-rail contact pressure could no longer be dismissed as of no consequence, nor could it be acknowledged and ignored. It had become sufficiently obtrusive and important to be both formally recognised as a force to be contended with and to be accorded its own name. And it was called 'hammer-blow'. This term was first used in the title of a published article in the Journal of the Franklin Institute during January 1887 and soon gained common acceptance and usage.[15] It is imprecise except in the special case when the centrifugal force generated by the balance weight in the driving wheel of a locomotive exceeds the static load on the wheel when the wheel will lift from the rail and impart a blow on its return. In normal locomotive operation this situation is not allowed to occur for obvious reasons. Nevertheless, at high rotational speeds of the driving wheel the alternate action of the balance weight in increasing and decreasing the contact pressure could be likened to a series of blows, and the general adoption of the term 'hammer-blow' enriched the vocabulary of locomotive engineering with another graphic but somewhat inaccurate expression.

Another consequence of alternating stresses induced in metals, that is, fatigue, had engaged the attention of engineers much earlier, serious concern following the first major railway tragedy. On 8 May 1842, the failure of a locomotive axle led to a disaster on the Paris-Versailles line which claimed fifty-five lives and badly injured more than a hundred other travellers.

The accident was attributed to fatigue.[16] Besides the thorough investigation carried out in France, the subject came to the fore in Britain. Papers on the subject were presented to the Institution of Civil Engineers in 1843 by W.J.M. Rankine,[17] and in 1854 by F. Braithwaite,[18] and to the Institution of Mechanical Engineers in 1849 by J.E. McConnell.[19] A summary of the early work on fatigue is given by S.P. Timoshenko.[20] Although recognised and discussed the topic never acquired the importance and prominence of 'hammer-blow' and was not treated as a separate issue by the Bridge Stress Committee in the 1920s.[21] The rapid cyclic variation of stress induced in laboratory specimens, by tests such as Wöhler's fatigue tests, was not considered representative of railway bridge loading under working conditions and, furthermore, the low working stresses used in bridge design were so chosen to make provision for possible fatigue effects, impact and other indeterminate factors.

2. The Safety of Iron Bridges

Towards the end of the nineteenth century the safety of iron bridges under the dynamic action of rolling loads was being questioned by civil engineers.[22] Although divided in their opinions on this topic, with some disputing any real significance of the effects of the speed of the rolling load with a properly maintained track others felt that in certain circumstances the very structure could be endangered in spite of the customary factors of safety. The balance weights of locomotives were identified as the cause of important variations

in vertical loads.[23]

The effects of synchronisation of the 'period of vibration' of a bridge with the 'period of application' of the loads had been observed and confirmed by experiments made for the State of Ohio Commission in 1884. Likewise experiments conducted by Baron von Weber revealed large increases in the stresses in bridge girders due to badly balanced locomotives. This cause was clearly specified as a matter of concern by the author of a paper read to the Institution of Civil Engineers at the turn of the century which provides evidence of the emergence of the problem on an international scale.[24] He cited two unnamed classes of British locomotives where the heavier, better balanced engines could pass over a bridge 'quite silently' and produce a smaller deflection in the girders than that of the lighter, badly balanced locomotives in their 'very noisy' passage across the structure.

While the last chapter has shown that during the first twenty years or so of the present century locomotive engineers in general did not optimise their opportunities to improve the degree of balance possible in locomotives, largely through adherence to, and seemingly rule-of-thumb application of, the Le Chatelier-Clark rule of 'two-thirds', examination of the evidence indicates that the same period was one of mounting anxiety for the civil engineers.

It is not the purpose of this study to examine the parameters and methods of bridge design but since the state of locomotive balancing practice on a nationwide scale was only laid bare as a consequence of the concern and investigations of

the civil engineers concerned with bridge construction and maintenance it is pertinent to note in passing the origins of their growing interest in the subject.

Briefly, the only guide to designers was the Board of Trade rule which in 1859 fixed the maximum permissible tensile stress at 5 tons per square inch for wrought iron. With the increasing use of mild steel as a structural material the Board of Trade regulations were amended in 1877 to raise the maximum stress for steel to 6.5 tons per square inch. These regulations did not appear to some engineers to make any provision for the extra stresses induced in girders by rapidly moving loads.[25]

The problem and the task confronting bridge engineers was described by W.B. Farr,

> It is of the highest importance that railway under-bridges should now be designed of such strength that they may not become obsolete in a short time owing to augmented loads on them from increasing weights of locomotives, etc., or from an underestimation of the effects of moving loads upon them, as has been the case in the past. Owing to want of knowledge on the part of designers of the earlier railway bridges, enormous sums of money have been spent, and indeed are still being spent, by railway companies in Great Britain, on the Continent of Europe, in the United States of America, in Canada, and in India and Australia, in reconstructing numbers of girder underbridges which have been taken down and replaced by stronger structures, not from

> reasons of wear or decay, but simply because they are incapable of carrying with safety the modern heavy rolling loads.[26]

The economic inducement to secure an improvement was obviously imperative and it is not surprising that an examination of existing procedures and an attempt to determine a rational method for 'impact' allowances should be made. Once again we find the vocabulary of the subject burdened by another inaccurate term. Although a 'live', quickly moving load running on to a bridge will have a dynamic effect, increasing the stress beyond what it would be if the load were stationary and for which some allowance must be made it was, and is, nevertheless an unfortunate expression. A scientific treatment of a topic is not assisted by an imprecise terminology and yet once coined and having won acceptance through widespread circulation and common usage such a word establishes its own right to existence, a right paramount over accuracy, common sense and logic. By the time of the publication of the Report of the Bridge Stress Committee, it passively accepted 'impact' with the tame comment, 'The name, though scarcely logical, is usual and convenient; it will be used throughout our Report.'[27]

Thus the body charged to put railway girder bridge design on a scientific basis acquiesced in its acceptance of the unscientific associated vocabulary.

In bridge design the Pencoyd formula[28] had been used in both India and the United States of America where the allowance to be added to the estimated train load was given by

$$\text{Impact allowance, } I = \frac{300}{300 + L}$$

where L is the span of the girder in feet.

The purpose of the formula was to determine the amount by which the live load, i.e. the estimated greatest train load, should be increased to allow for impact.[29] Hence for a span of 300ft the train load is increased by 50 per cent and as the span decreases the impact allowance approaches a limit of unity. In other words, when L = 0 the train load is doubled, a result which conforms to the simple approximate analysis which shows that a suddenly applied load produces a stress double that induced by the static application of the same load.

Various formulae of this kind were in use and details of them are to be found in both Cassier's Engineering Monthly[30] for September and October 1915 and in the Bridge Stress Committee Report.[31] Fig.6.1,[32] taken from this latter document, shows the wide variation of allowance, the only consensus being on the inverse ratio of allowance to span. For example, while the Pencoyd formula gives an impact allowance of 50 per cent on a span of 300ft, as noted above, the Fyson formula yields an allowance of approximately one tenth of this. The other formulae, in general lying between the limits represented by these two curves, distribute the allowance over the wide intermediate range in such a way as to bewilder the designer seeking guidance. Such significant differences are probably due to the basic assumptions on which the individual relationships were formulated. Although the various formulae no doubt

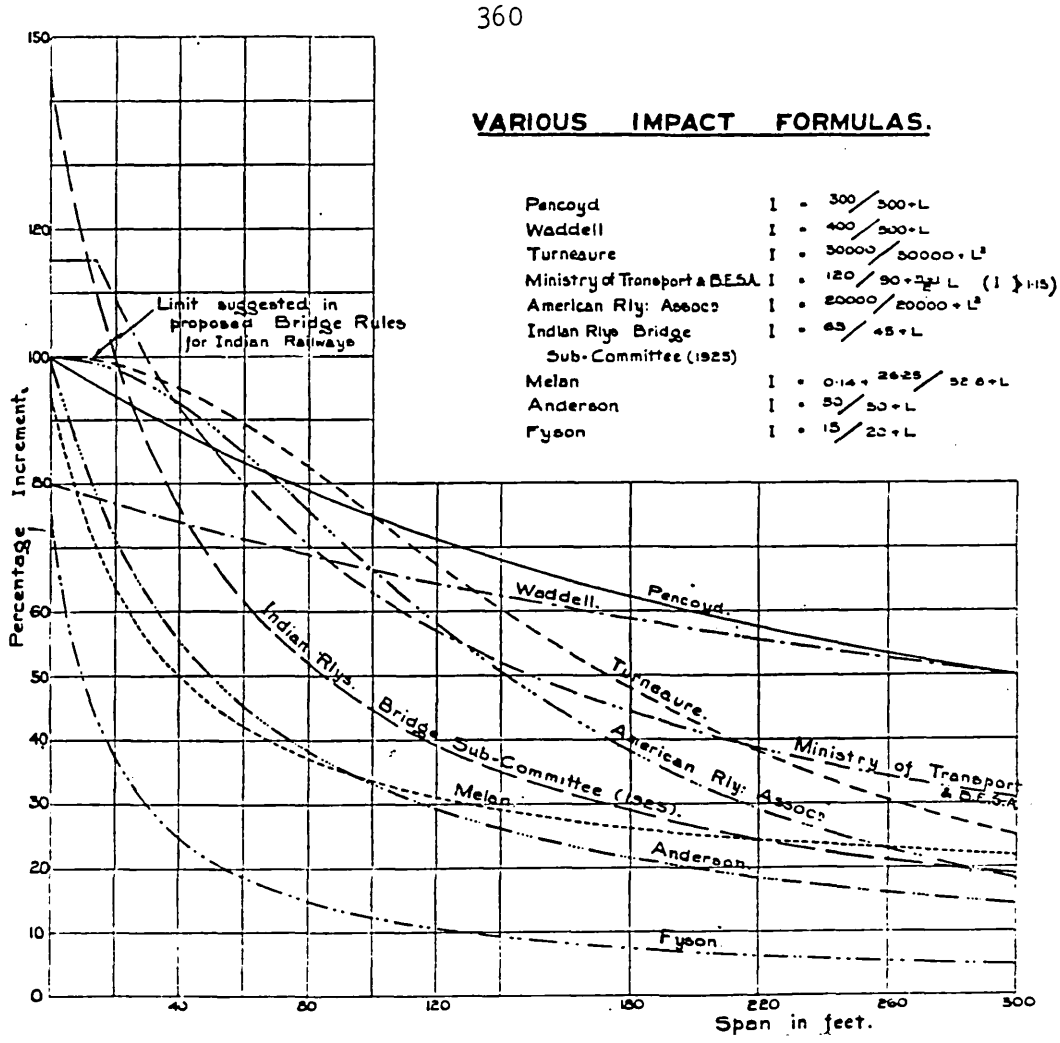

VARIOUS IMPACT FORMULAS.
Pencoyd I = 300/(500+L)
Waddell I = 400/(500+L)
Turneaure I = 50000/(50000+L²)
Ministry of Transport & B.E.S.A. I = 120/(90+3/2 L) (1 ½ H15)
American Rly: Assocn I = 20000/(20000+L²)
Indian Rlys Bridge Sub-Committee (1925) I = 65/(45+L)
Melan I = 0·14 + 26·25/(32·6+L)
Anderson I = 50/(50+L)
Fyson I = 15/(20+L)
Limit suggested in proposed Bridge Rules for Indian Railways
Percentage Increment.
Waddell.
Pencoyd.
Indian Rlys. Bridge Sub-Committee (1925).
Turneaure.
American Rly: Assocn.
Ministry of Transport & B.E.S.A.
Melan.
Anderson.
Fyson.
Span in feet.

Fig.6.1 Curves illustrating various impact formulas

satisfactorily met the conditions which initially led to their adoption, the passage of time revealed weaknesses and inadequacies and, in some cases, led to modification.

Criticism was made of the Pencoyd formula in the two countries where it was widely used on the grounds that the allowances it made on the smaller spans were deficient and on the larger spans, excessive.[33] Mounting suspicion of their validity and increasing dissatisfaction with the derived results directed the attention of engineers and, as mentioned above, of those footing the bills, to the need for further investigations.

During 1907-1909 an extensive series of experiments on bridges in the United States was conducted by the American Railway Engineering and Maintenance of Way Association and its report was issued in 1910. The Russian Rail Commission of 1912-1914 was engaged in similar activities.[34] In 1915, in a paper entitled 'On Impact Co-efficients for Railway Girders' the author stressed before a British audience the special interest of the subject because of

> lack of recent experimental data which would assist in the formation of more positive conclusions than at present exist as to the proper allowance to be made for the dynamic effect of moving loads.[35]

In 1917 a Committee was appointed by the Indian Railway Board, whose work lasted throughout several years and resulted in the publication of five reports between 1917 and 1921.

Thus we can see there was a mounting world-wide pressure to cope with the problem of the dynamic effects of locomotives and rolling stock on railway bridges. Whilst the locomotives were the chief offenders they were not the only source of trouble and W.B. Farr, in his paper referred to earlier, recounts his own observation of the wagons of a goods train, where the axles were about equally loaded as well as equally spaced, bringing about a near resonant vibration at moderate speeds which did not occur at higher speeds.[36] Thus more vibration could be caused by the train than by its locomotive. When, after the end of the First World War, the Ministry of

Transport took some action in this matter it was a late involvement in a movement which had much earlier origins. And it is arguable that but for the war, which put the railways under Government control, the large scale inquiry which revealed the extent of variation in impact allowances and permissible stresses in bridges would not have been conducted. In this pre-Grouping era, when virtually every company adopted codes of practice to meet its own perceived requirements uniformity of provision in civil engineering matters was clearly as individualistic as was the provision of locomotive power. This almost chaotic state was obviously unsatisfactory and was so to the extent that even a uniform system of replies to the inquiry was unattainable.[37] In the attempt to rectify this situation the Railway Engineers' Association immediately set up a committee to review the matter and make appropriate suggestions. Recommending experiments to verify its suitability, the committee advised the immediate general adoption of the Pencoyd formula in this country to achieve a uniformity of practice with respect to the allowance for impact. This seems to be incontrovertible evidence of the seriousness of the situation in the view of the Association and, despite its call for verification, also a measure of its desperation. Advocacy of the adoption of a parameter under suspicion in the two countries where it had been extensively used - and where concerted efforts were being made to discard it in favour of something better - suggests that a somewhat deficient uniformity was regarded as superior to the existing state of unknown diversity. Activity now reached a feverish pitch. The Ministry of Transport also

set up a committee, under the chairmanship of Colonel (later Sir) John W. Pringle, the Chief Inspecting Officer of Railways, which suggested that the Ministry should conduct more tests. Simultaneously the British Engineering Standards Association appointed a committee to produce a standard specification for the design of girder bridges and this body too, called for further experiments but, in the event, they were not performed. However, tests organised by the Ministry of Transport were carried out during the summer and early autumn of 1920 and the results were published during the following year in the report of Major A.H.L. Mount.[38]

3. Ministry of Transport Tests on Railway Bridges

The work of the committee must be viewed as a preliminary exercise and a reasonably large-scale preparation for the full-scale investigation that followed. Its aim was the prompt establishment of a common design practice until a more thorough and comprehensive examination of the matter had been completed. Certainly its own initial survey had revealed a wide divergence of practice among the Railway Companies in allowing for impact. Some related the working stress (the maximum permissible being 6.5 tons per square inch) to the span, others employed a range of stress formula, while yet others - a minority - made no allowance at all. In these circumstances its task, stated in its terms of reference was

> To determine...some formula or curve giving the minimum desirable increments for impact to form the basis for

calculation of stress in the immediate future.[39]

The achievement of even this limited objective provides us with some understanding of the complex issues involved in securing an acceptably successful locomotive-track, and especially a locomotive-track-bridge, working relationship. And, furthermore, why success was so long in coming. Generally, the view is held that until the grouping of the railways in 1923 the railway system of the nation was composed of many companies, large and small, each concerned with its own problems and, technically, designing its own locomotives and its own civil engineering projects to meet its own needs, its own needs as perceived by the personnel involved rather than on the basis of a rational assessment. Additionally, the organisation of the companies was such that cooperation between the civil and mechanical engineering departments far from being close was frequently minimal to the point of being almost non-existent. Moreover, it is not unreasonable to assume that the companies lacked the financial resources quite apart from the incentive to prosecute scientific investigations which probably, in the views of Boards of Directors, had little to contribute to the profitability of the enterprises. 'Research and Development', an essential function and characteristic of many twentieth century technologies cannot be regarded as, nor was it in fact, an integral part of the railway system.

In organising the tests the Committee needed the cooperation of railway companies in making available suitable bridges, locomotives, dynamometer cars and staff. It also had

to negotiate the loan of the necessary stress recording instruments, supplied by Messrs Rendel, Palmer and Tritton, and arrange for the services of experienced staff to use them.

Instrumentation was, in itself, a specialised requirement essential to a meaningful investigation of the kind undertaken and one not without its own problems which, however, produced both experience and enlightenment which were to prove of value a few years later in the work of the Bridge Stress Committee. Amongst a variety of difficulties encountered in association with calibration, datum errors, instrument mounting techniques and the effects of temperature variation perhaps the most significant, in the exercise being carried out, was the natural frequency of the stress recorder employed. In the measurement of vibration it is important to use an instrument whose natural frequency is not in the range to be measured. The tests revealed a coincidence of instrument and structure frequencies with certain types of troughing and rail-bearer members with the consequent effects of resonance yielding unreliable results. Appendix 1 of the Report is devoted to Fereday & Palmer's Patent Stress Recorder. This instrument was again used by the Bridge Stress Committee.

The tests on twenty steel bridges, selected as being typical of British practice, with spans ranging from 15'0" to 146'8", were performed on the lines of, and with locomotives provided by, the following companies:

South East Chatham Railway

Great Western Railway

North Eastern Railway

London and North Western Railway

Attendance at the tests of representatives of other railway companies, including the Great Eastern, Great Northern, London and South Western, Midland, Caledonian plus the Chief Engineer of the Indian Government Railway Board, amongst others, testifies to the importance attached to them.

Selection of the locomotives was not on known 'hammer-blow' characteristics but rather

> The engines were of typical two-cylinder passenger type, chosen from approximately the heaviest working on each system.[40]

Thus, we can see that the selection was on a dead-weight basis and as such was a choice which vitiated the results. Limitations of the work done and the results obtained were recognised and acknowledged in the Report. Since speeds in passenger traffic greater than those employed in the tests (55-65 mph) were not uncommon the report conceded that

> ...greater impact effect than that recorded is quite likely to result under ordinary running conditions. Moreover, no steps have been purposely taken in these

> tests to locate engine driving wheels in their worst positions, so it is improbable, for this reason also, that maximum results have, in any case been attained.[41]

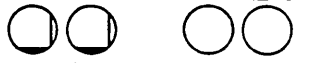
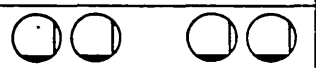
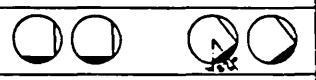
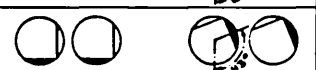
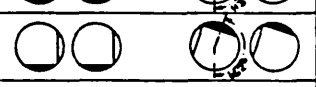
Many of the trial runs were made with two locomotives coupled together and hauling a dynamometer car or a coach and on those conducted on the North Eastern Railway, by means of a contact on the slide bar, the relative positions of the balance weights on the two engines were recorded. See Fig.6.2[42] which shows the presentation of results for Maunby Bridge, together with Fig.6.3[43] which gives the corresponding deflection records.

Implicit in the work of the Committee is the assumption that the heaviest locomotives would give the greatest impact effects and there appears to be no recognition that the dynamic behaviour of the machines, in the sense of well-balanced as opposed to badly-balanced engines, not only was a major cause of the trouble but also offered the potential for reducing the magnitude of the impact forces. The dynamic properties of the locomotives used were not referred to and there is no suggestion in the Report that it would have been helpful to have this information. It tabulated both the calculated and recorded stress due to static live load and noted 'in nearly every case, the instrument has read less stress than was calculated for'.[44]

In view of this it cautiously stated that the methods of calculation provided 'plenty of margin for safety'!

Bearing in mind that two of the companies participating in the exercise, that is, the Great Western Railway and the North Eastern Railway, operated four-cylinder and three-cylinder

BRIDGE Nº101. LEEDS NORTHERN.
N.E.RLY.

Nº of Test	Speed in Miles per Hour	Stress in Tons per Sq. In.			Impact %			Mean Location of Balance Weights of the two Engines. when on the span	Remarks.
		Main Girder Bottom Boom nest Panel to ℄.	Main Girder Bottom Boom 2nd Panel from end	Main Girder Top Boom at ℄.	Main Girder Bottom Boom nest Panel to ℄.	Main Girder Bottom Boom 2nd Panel from end	Main Girder Top Boom at ℄.		
133	CRAWL	·95 *		1·85 ± 5	–		–		
134	35·3	1·36 ± 15		1·96	40 ± 15		5 ± 3		
135	52·4	1·57 ± 7		1·95 ± 6	(92 ± 7)		5 ± 6		Not Located
136	55·2	1·84 ± 6		2·00 ± 7	55 ± 6		8 ± 7		In Phase
137	48·4	1·45		2·10	50		(13 ± 2)		
138	46	1·27		2·00	31		8 ± 2		
139	CRAWL	1·00 *	·87 ± 10		–	–			
140	31	1·22	1·25 ± 22		26	44 ± 40			
141	44·4	1·25	1·31 ± 10		29	(51 ± 30)			
142	56·8	1·45	1·27		48	46			
Calculated Static Stress due to Dead Load		1·82	1·75	1·44					
Calculated Static Stress due to Live Load		2·76	2·70	2·18					
Nº of Test		133	134	135	136	137	138	135 / 140 / 141 / 142	
Deflection in Inches		·710	·741	·786	·780	·725	·725	·694 / ·718 / ·716 / ·694	

Calculated Critical Speed 47 m.p.h.

Observed Critical Speed 46 to 52 m.p.h.

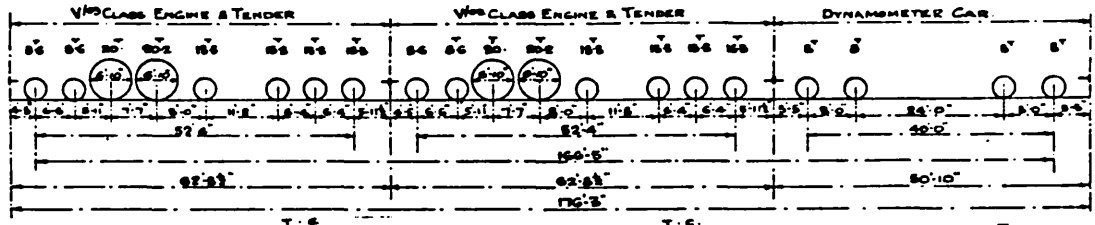
* Mean of Crawl Stresses = ·97 v. 133 & 139.

Fig.6.2(a) Results of Tests on Maunby Bridge
North Eastern Railway

STEEL BRIDGE No 101. (MAUNBY BRIDGE) LEEDS NORTHERN. DOWN Road

DESCRIPTION. Two Main Girders (Linville type) Cross Girders, Rail bearers, Longitudinal rail timbers carrying a double track. Effective Span 146'8"
Main Girders 27'6" apart centres. Cross Girders - effective span 27'6"
Cross Girders 12'0" apart centres.
Rail-bearers - effective span 12'0".
Superelevation 1/2". High rail adjacent to Main Girder - Down Road.
Gradient - Rising 1 in 1360 up to Bridge.

TEST LOAD USED.



TOTAL WEIGHT OF ENGINE 76-4 T.C.
" " " TENDER 45-6 T.C.
TOTAL WEIGHT OF ENGINE & TENDER 121-10 T.C.

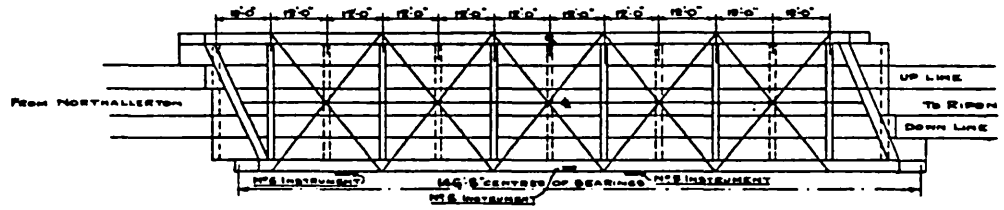
TOTAL WEIGHT OF ENGINE 76-4 T.C.
" " " TENDER 45-6 T.C.
TOTAL WEIGHT OF ENGINE & TENDER 121-10 T.C.

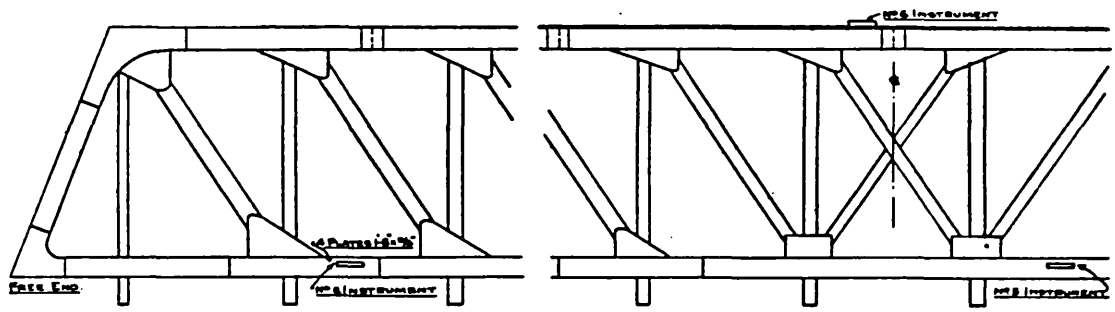
TOTAL WEIGHT OF CAR 32 T

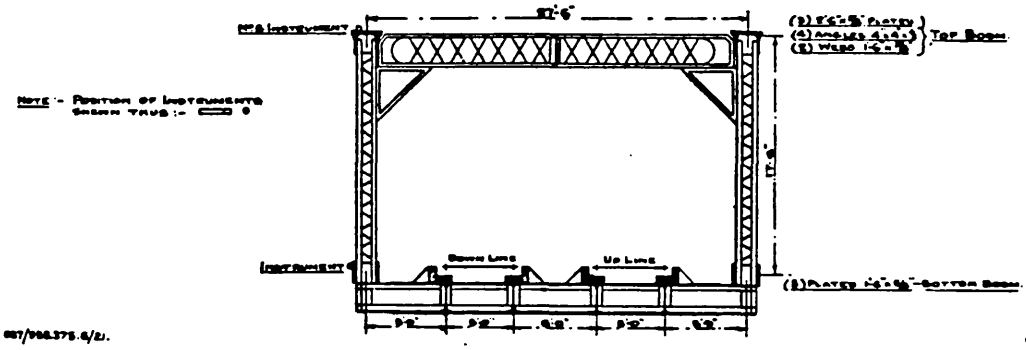
TOTAL WEIGHT OF TWO ENGINES & DYNAMOMETER CAR 275 T

EQUIVALENT UNIFORMLY DISTRIBUTED LIVE LOAD PER FOOT RUN OF TRACK 192 T
" " " " " " TRACK 282 T
" " " " " ON DOWN SIDE GIRDER 196·4 T

DEAD LOAD ON DOWN SIDE GIRDER 124·5 T
RATIO OF DEAD TO LIVE LOAD 0·634.







NOTE :- POSITION OF INSTRUMENTS SHOWN THUS :-

Fig.6.2(b) Details of Test Load Used and of the Bridge

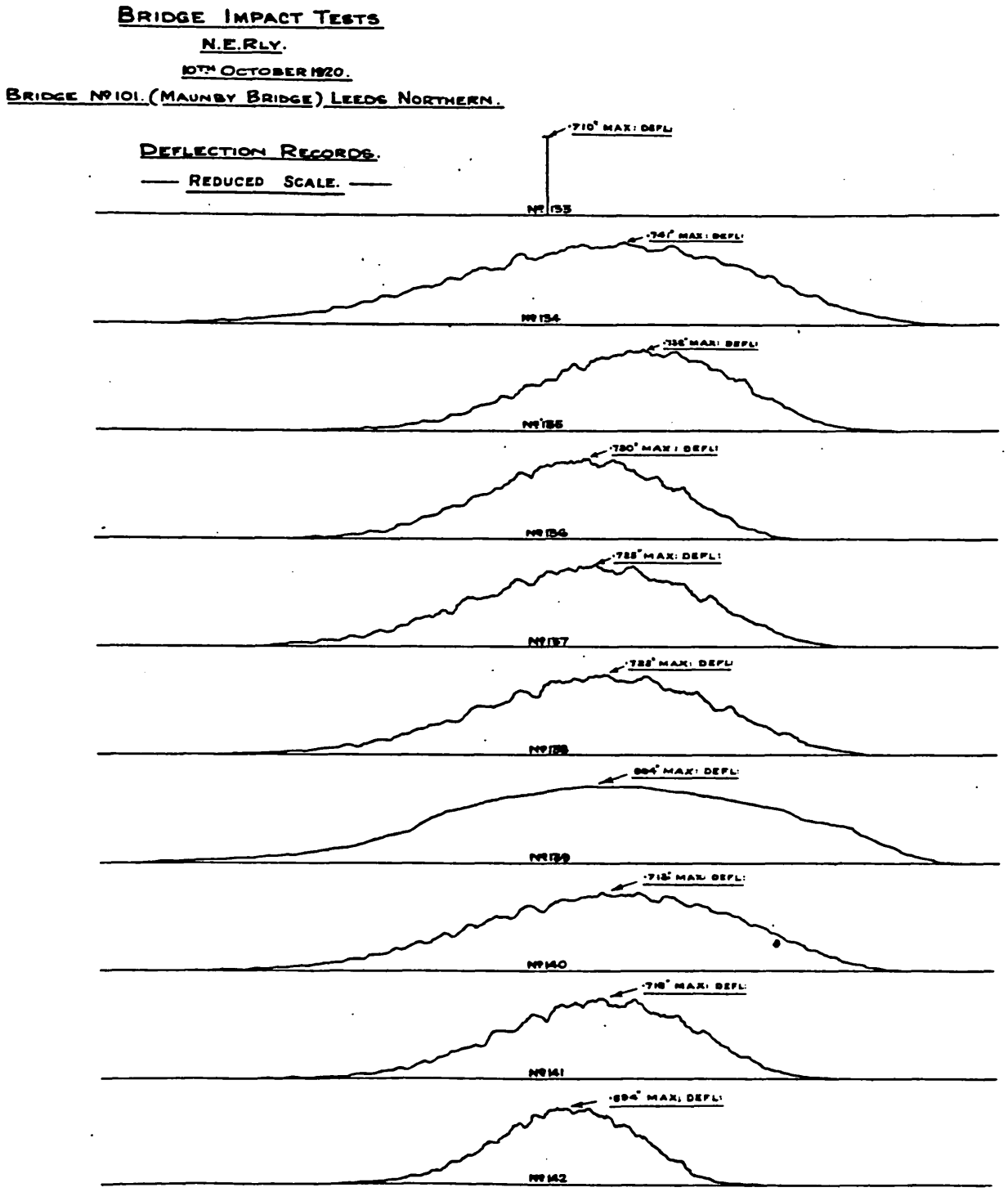


Fig.6.3 Deflection records, Maunby Bridge

engines respectively the decision to limit the trials to two-cylinder locomotives exclusively is not without interest. Unfortunately the historian relying on official reports for his

evidence is confronted with a vexatious problem. Such documents tend to state what was done without giving the reasons and yet, in some cases, as for example in the matter under discussion here, the reasons would be of equal, if not greater, interest.

Undoubtedly, two-cylinder locomotives in service vastly outnumbered the three- and four-cylinder varieties and from this point of view they represented the norm and additionally, since weight was the stated criterion in selection, they were not significantly different in this respect.[45] The notion that three- and four-cylinder locomotives were inherently better balanced machines than two-cylinder engines may also have been held by those responsible for making the choice. Without a detailed knowledge of the topic this would not have been an unreasonable assumption but, as the previous chapter has shown, there was not a comprehensive understanding of the subject. Civil engineers, in general, were not aware of, nor interested in, the dynamics of locomotive behaviour. Furthermore, it did not follow that they were necessarily better-balanced and in due course the work of the Bridge Stress Committee revealed the existence of four-cylinder engines with greater hammer-blow than two-cylinder locomotives.

The final recommendation of the Report was the offering of a formula for impact allowance which was but another variant on the form of the Pencoyd formula, that is

$$I = \frac{120}{90 + L}$$

This curve is also shown in Fig.6.1.[46] As will be seen from the diagram it answers the criticism of the Pencoyd formula insofar as it increases the allowance for short spans and reduces the excess in long spans but it is obviously of identical form and susceptible to the same charge that it lacked any sound scientific basis.

Something approaching a crisis situation is clearly indicated by the very formation of the committee. Both the size and increasing importance of the task of strengthening bridges plus the revelation of such diversity of practice throughout the country were obviously of great concern to the Ministry of Transport but the approach to the problem was essentially a perpetuation of the old philosophy. Bridges and their design, construction and maintenance were the business of civil engineers. An awareness of the fundamental and inseparable functional inter-relationship between the two had not dawned. Thus the work of the Committee was undertaken by civil engineers to produce some results of immediate value in bridge engineering. The dynamic behavioural properties of the locomotives were not known, nor does the report intimate any hint of recognition that such information was pertinent or could have been of value inasmuch as the attempt could have been made to relate the behaviour of the bridge to that of the locomotive. Although the relative positions of locomotive balance weights were ascertained for the tests conducted on the North Eastern Railway the Report does not give any reason for doing so nor does it appear to correlate these with the associated deflection curves. In these trials the locomotives were almost certainly

regarded as structure-loading devices and the task to be fulfilled was the provision of bridges strong enough to permit the safe passage of locomotives (of unspecified dynamic characteristics), together with their trains. This was accomplished in this exercise by determining the impact effects of a representative number of locomotives on a representative selection of bridges, by plotting these on a graph of 'Impact Increment Percentage to Live Load' against 'Length of Loaded Portion' and determining an enveloping curve which avoided the perceived deficiencies of the Pencoyd curve. The Committee offered two impact formulae[47] for consideration following its investigations, viz.

$$I = \frac{75}{L+50} \qquad \text{and} \qquad I = \frac{120}{L+90}$$

but clearly felt that the second of these was most representative of its results.

Subject to certain qualifications this formula was incorporated into the British Standard Specification for Girder Bridges[48] but its value was seriously questioned by The Railway Gazette.[49] In paying tribute to the experimental work of the Committee this journal opined that the meagre data confirmed the value of the Pencoyd formula rather than justified either of the two put forward in the Report and suggested that they should be cautiously accepted.

Based on this valuable piece of evidence, and in retrospect, it is not unreasonable to conclude that the approach

of the Ministry of Transport and its officers and the other engineers involved did not envisage a cooperative effort to provide a 'systems' solution to the problem. Indeed the Report did nothing to advance design procedure but merely offered the reassurance of another impact formula specifically derived to meet British requirements. Their results, albeit only offered as an interim measure, were of questionable value. Indubitably the true significance of the work of the Committee was its articulated cognisance of the need for a wider and more thorough investigation if the subject was to be placed on a scientific basis, combined with an unmistakeable indication of the magnitude and nature of the task to be undertaken.

4. The Bridge Stress Committee and its Work

The momentum of this burst of activity in the early 1920s was maintained and impetus was added by the involvement of the Department of Scientific and Industrial Research. In May 1922 this Department convened a meeting of railway engineers and others as a result of which arrangements were made for conducting an inquiry and led in March 1923 to the appointment of the Bridge Stress Committee. Besides being charged with the continuation of the earlier work of the Ministry of Transport on impact effects this committee also had the duty to carry out, concurrently with the experimental work, mathematical investigations, a requirement which was reflected in the composition of the membership. Under the chairmanship of Sir J. Alfred Ewing, Principal and Vice-Chancellor of the University of Edinburgh, the committee consisted of representatives of the

four Grouped railways, a consultant engineer, the Chief Inspecting Officer of Railways, Professors W.E. Dalby and C.E. Inglis and Mr R.V. Southwell, a mathematician.

An examination of the list of members of the Committee reveals an absence of locomotive engineers.[50] This is, perhaps, a surprising omission in view of Lord Balfour's comment in his Introductory Note that 'Fixed bridges and trains in motion become for brief periods parts of a single mechanical system.'[51] Even more surprising is the statement concerning the subsequent invitation to Sir Henry Fowler to become a member.

> At a later stage the Committee, finding that the problem was intimately connected with questions of locomotive design...[52]

a pronouncement which suggests that at the beginning of the work the eminent civil engineers representing the railway companies were still unappreciative of the nature of the problem they were trying to solve. Confirmation of this view seems to be afforded by the incidents related in the previous chapter of the emphasis of civil engineers on static axle loads and an apparent total neglect of the dynamic forces brought into action by the motion of the locomotive. Obviously one or two isolated cases and examples do not provide conclusive proof but it is the only evidence which this piece of work has brought to light and in the absence of contrary evidence it appears reasonable to accept the situation on two large British railway companies, that is the Great Western and the London and North Western, as typical

of the general 'state of the art'. Verification of this interpretation of the evidence is provided by the comment of Conrad Gribble, in the introduction of his paper to the Institution of Civil Engineers on 5 March 1929.[53] This man, the Chief Engineer responsible for the field work carried out by the Bridge Stress Committee, stated that even in the absence of a less definite result the research carried out would have been useful for a number of reasons, and of those he mentions priority of position is accorded to the sentence

> It shows the effect on the oscillations of bridges of two factors that have not previously been fully considered in relation thereto, namely, the hammer-blows of the unbalanced parts and the frictional resistance of the spring-gear of locomotives.[54]

Even when, at a later stage, it was recognised and acknowledged that the locomotive was an essential component in the system being investigated the opportunity was not taken to secure a wider representation of mechanical, as opposed to civil engineers. And in this respect the composition of the Committee was unbalanced. Whereas the civil engineering departments of the four companies were represented, Sir Henry Fowler was chosen to represent locomotive engineering for the whole country. In view of the marked regional differences in locomotive design and practice this was, perhaps, a surprising decision. It was unquestionably a failure to seize the opportunity to bring the Chief Mechanical Engineers of the four companies into immediate

contact with the work of the Committee, to the direct and unmediated benefit of their departments. Such a step would also have brought the civil and mechanical engineers of each of the companies together in the consideration of a common problem and in so doing given them a new experience and an example of the usefulness of cooperative endeavour on issues of common interest.

The limitation of locomotive interest to a solitary engineer makes the selection of Sir Henry Fowler an interesting topic for speculation. The four Chief Mechanical Engineers then in office, C.B. Collett, H.N. Gresley, G. Hughes and R.E.L. Maunsell, were, with the possible excepton of Collett, all interested and directly involved, in the design of locomotives and yet the choice fell upon one outside their ranks and one, furthermore, whose interest in design if not non-existent was undoubtedly minimal.[55] Although but conjecture, it is quite likely that when it was decided that such a nominal, representative, appointment was desirable the choice was based on the eminence of Sir Henry as an engineer who had been knighted for his contribution to the war effort, rather than for his expertise in locomotive affairs.

As has just been discussed, with its single 'locomotive' representative the Committee was from its inception and remained, overwhelmingly, a civil engineering body. Its field work conducted under the supervision of C. Gribble, was performed by a team of engineers together with a photographer and a clerk,[56] and consisted mainly of deflection and stress determination in bridge-structural members under specified

conditions of loading. This aspect of the work will not be considered here because details of it, besides being found in the Report itself, are summarised in Gribble's paper[57] referred to earlier.

However, a brief summary of its work is necessary to give an indication of its relevance to locomotive engineers and its unmistakeable demonstration of the fundamental relationship between engine and structures over which it was to run.

4a. Aims

The wide terms of reference under which the Committee was appointed were 'To conduct researches with reference to the stresses in Railway Bridges, especially as regards the effects of moving loads.'[58]

Intended as a continuation of the Ministry of Transport Committee's investigations, the Bridge Stress Committee defined and limited its own role to

> ...our immediate task was to elucidate the question of "impact" stress by examining its actual character and causes. These were felt to be somewhat obscure, not-withstanding all the attention the subject had already received.[59]

Practically, the main objective of the exercise was to provide bridge designers with a rational means of making an allowance for impact as an additional load on the structure. A modified, more accurate empirical formula of the Pencoyd and

Ministry of Transport types, universally applicable to all bridges carrying any type of locomotive, was not envisaged. Through the concurrent prosecution of experimental field work and scientific analysis it was hoped to reach a proper understanding of the causes of impact, its effects upon bridges and to produce a scientifically-based method of catering for it in the design process. Increments to the dead weight to be carried, for this purpose, based simply either on the span of the bridge or the weight of the engine itself, were obviously imprecise and in a rational analysis of the matter could hardly be justified. That many bridges formerly built or strengthened in accordance with the old empirical forumlae had successfully carried loads far in excess of those for which they were designed was no reason for their continued use as design parameters. This success was attributable largely to the sound instinct of their engineers to produce 'safe' structures, through the use of large factors of safety to cope with the various indeterminate loading conditions. Commendable and essential as this precaution was and, indeed, must ever remain where human life is involved the method used possesses inherent limitations. These had begun to manifest themselves with accelerating urgency from the beginning of the present century. After some ninety years' public railway operation in the country it was accepted, through force of circumstances, that the utility of empirically determined formulae and rule-of-thumb procedures had been exhausted. Their inability to cope adequately with contemporary requirements was serious, and inordinately expensive in financial terms, while their deficiency

in scientific foundation rendered them useless for purposeful, economic future design.

To remedy this situation the Bridge Stress Committee aimed at a fundamental improvement both for the immediate benefit of the railway system and from which future development could confidently and successfully progress. In fulfilling its mission it gave locomotive engineers a salutary lesson.

The inestimable value of the Committee's work for the purposes of this study is that it chose the locomotives to be employed on the basis of their dynamic behaviour. Whereas the Ministry of Transport tests were confined to two-cylinder passenger locomotives selected on the basis of dead-weight alone the Committee's investigations were to cover different types of engines including two-, three- and four-cylinder varieties. And the railway companies were specifically requested

> ...to provide for testing purposes engines capable of producing large variations of rail pressure, in order that the oscillations produced, and the effects of these oscillations, might be thoroughly investigated.[60]

Selection, however, was not based on quantitative knowledge in other than a minority of cases, where the magnitude and direction of the resultant unbalanced forces had been determined on a balancing machine during the construction of the locomotive. For most of the engines these measurements were made at the request of the Committee from which we may conclude that the practice of putting into service locomotives whose

dynamic characteristics were unknown was a common occurrence.

The engines, then, were the loading devices and supplemented with a 'bridge-oscillator' they produced the effects measured and recorded in the tests and from which the conclusions were derived. Fifty-two bridges, representative of British practice but excluding special and obsolete designs, with spans ranging from 16.5 feet to 345 feet were used in the tests.[61] Some of them were of wrought iron construction and the report in acknowledging that this material was seldom, if ever, used in contemporary construction, justified their use on the assumption that steel and wrought iron bridges could be expected to respond identically to impact effects.

b. Experimental Work

The following diagram, Fig.6.4,[62] is typical of many records included in the Report, which in turn contains only a representative selection of those made during the field work.

The two curves show the deflection against time of mid-span of the bridge, Maunby Bridge - for which Ministry of Transport test details have been included earlier (Fig.6.2 and 6.3), due to the passage of two locomotives. The horizontal scale at the top of the diagrams represents time, calibration being in tenths of a second, omission of the tenth mark indicating a complete second.

Locomotive AG, travelling at a speed of 36.7mph, produces a gradual deflection and restoration with little vibration although the effects of individual hammer-blows may be discerned. With locomotive K, at 33.0mph, the correspondence of

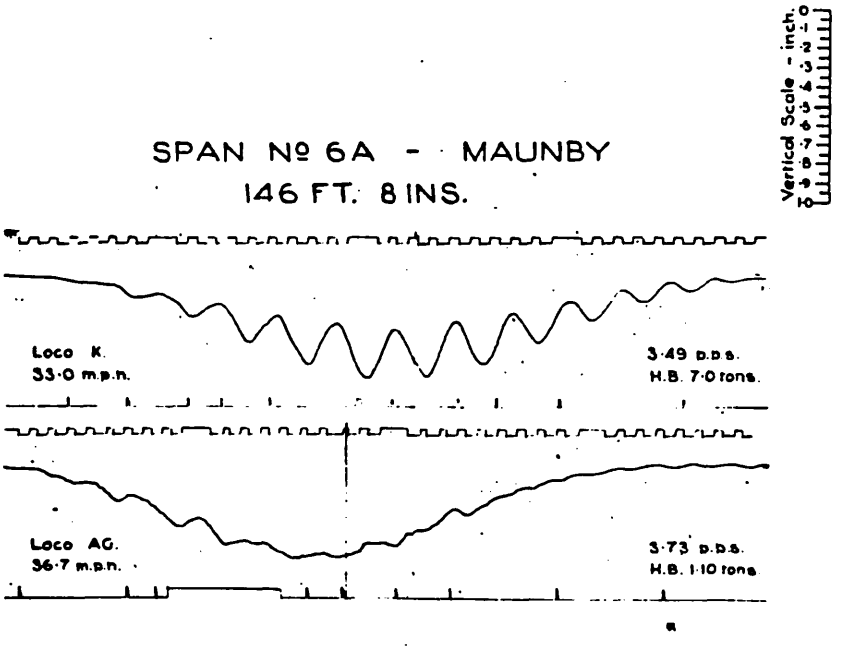


Fig.6.4 Deflection record, Maunby Bridge

this, its critical speed, with the natural frequency of the bridge produces through the action of the hammer-blow, a gradual build-up of the oscillations to a state of resonance. The decaying oscillations on the right of the diagram signify the passing off the bridge of the locomotive and the effects of damping. Thus the effects of hammer-blow are magnified by resonance, a state induced by the coincidence of a critical speed of the locomotive and the natural frequency of vibration of the bridge. Similarity of the natural frequencies of bridges, except the extremes of span length, i.e. the shortest

and the longest, and the frequency of hammer-blows from engines at ordinary speeds is fairly common and thus made this situation one to be seriously considered.

The inherent high natural frequency of short span bridges and the relatively low frequency of hammer-blow input, even by locomotives travelling at express speeds gives rise to an entirely different situation. Resonance and its effects are completely eliminated. But in such cases each hammer blow produces a distinct individual effect. This is shown in Fig.6.5,[63] the deflection curves for the two girders of Newby Wiske bridge, with a span of 44ft 8in, under the action of locomotive K.

Because the natural frequency of vibration of a bridge is inversely proportional to its span the conditions for resonance are more readily attained in long bridges than in short ones but in the long lengths, as opposed to those of intermediate span, the phenomenon is not so serious. In this case the natural frequency is low and the corresponding critical speed of the locomotive is also low with the consequence that the hammer-blow forces which induce the vibrations are also small. The following diagram, Fig.6.6,[64] shows the effects of running locomotive K at various speeds over Newark Dyke Bridge, a single track lattice girder bridge of 262ft 6in span. As the locomotive speed increases from 2.14cps the build-up of oscillation is clearly seen on the deflection curves until at a frequency of 2.4cps, which is also the natural frequency of the loaded bridge, a state of resonance exists. With further increases of speed the engine moves out of its critical speed

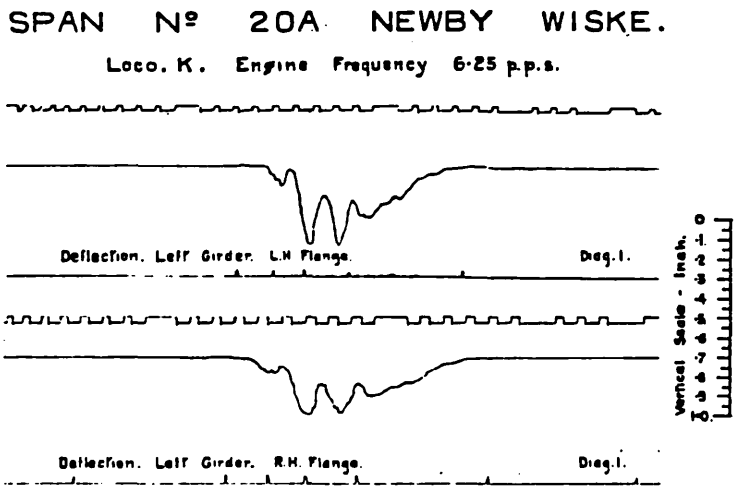


Fig.6.5 Deflection record, Newby Wiske Bridge

range and the effects of hammer-blow in generating vibrations within the structure rapidly diminish.

Reference has been made earlier to a 'bridge-oscillator' as a loading device. This is shown in Fig.6.7[65] taken from Appendix H of the Report.

As may be seen it consists of a truck on which is mounted a frame carrying a pair of contra-rotating axles, each bearing two wheels to which could be attached weights whose magnitude could be varied to simulate any desired amount of hammer-blow. The purpose of this piece of equipment was

...to apply a pulsating force to a bridge for an unlimited number of times without any change in the position of the load or variation in frequency of the structure.[66]

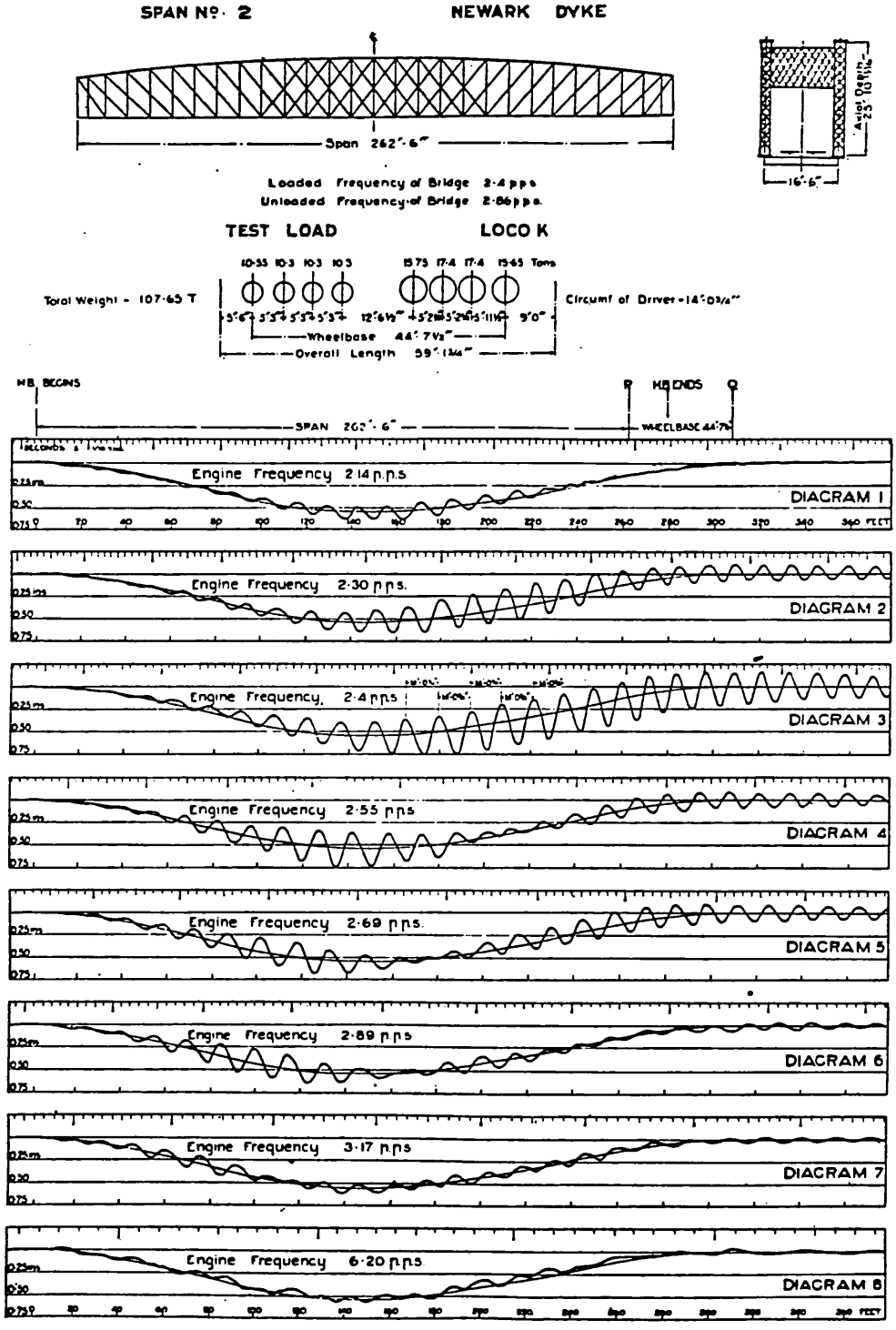


Fig.6.6 Deflection curves, Newark Dyke Bridge

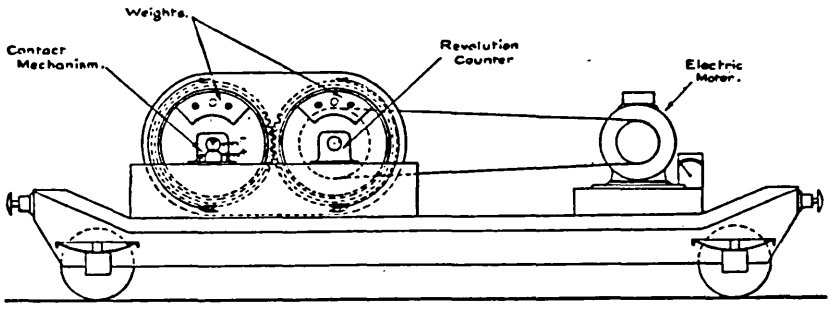


Fig.6.7 Bridge-oscillator

It was thus an extremely useful device permitting amongst other things a study of resonance and its effects not attainable with a moving locomotive. Because of the motion of the engine and hence a variation in the system of loading on the bridge its natural frequency would not remain constant during the passage of the vehicle and the maximum vibration of the structure could not be attributed to a specific critical velocity but rather to a limited range of speed.

By jacking the oscillator off its springs and clamping it solidly to the rails it was used to determine the natural frequency of the longer bridges in both their loaded and unloaded conditions.

Deflection readings, taken on the River Aire Bridge, with different weights mounted on the wheels to give different hammer-blows clearly indicated, within the limits of experimental error, a direct proportionality between the amplitude of the vibration and the magnitude of the hammer-blow,

as will be seen from Fig.6.8.[67]

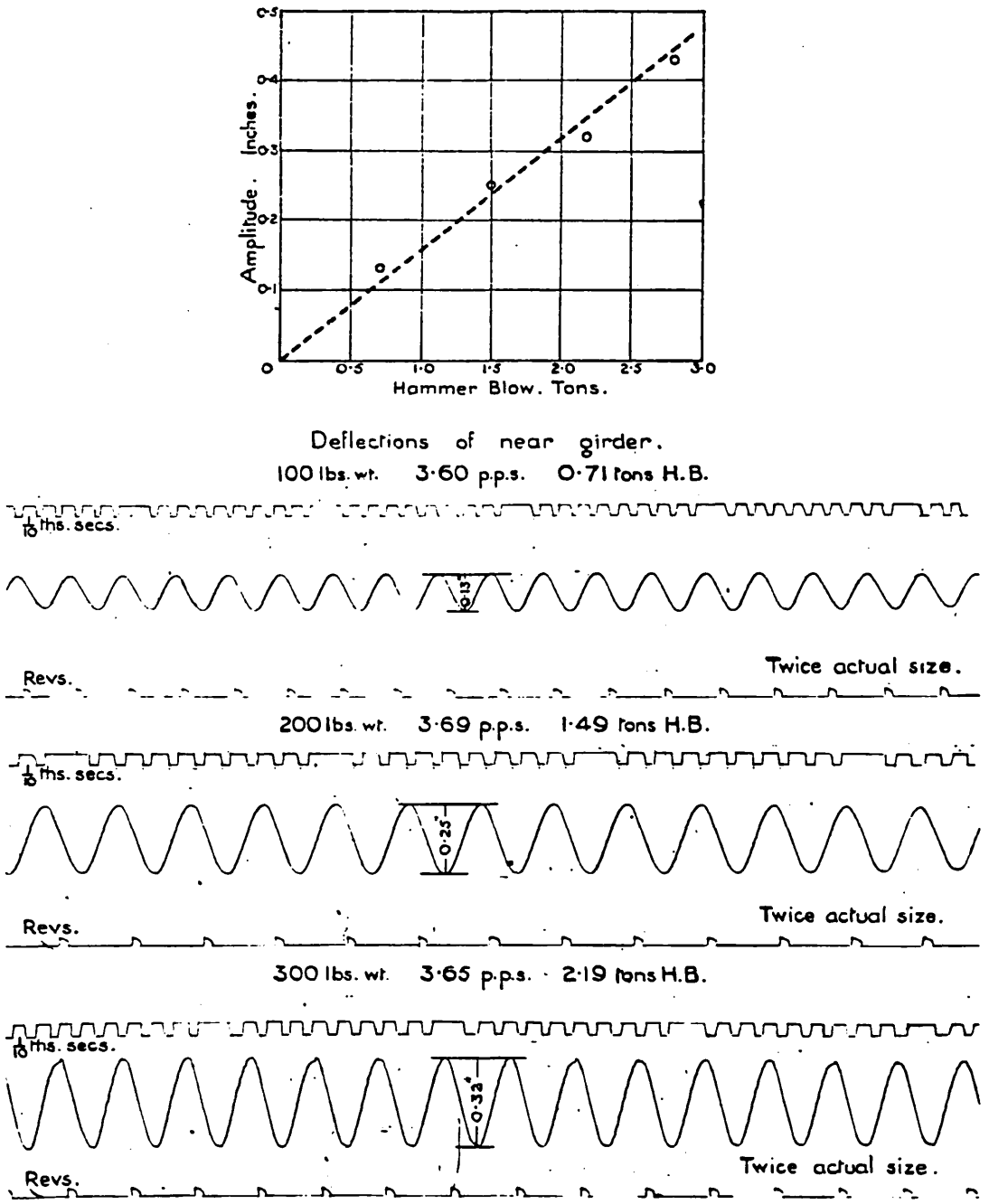


Fig.6.8 Oscillator records, River Aire Bridge

Whatever reservations were intially entertained by the members of the Committee as to the true causes of impact these experimental results undoubtedly established that hammer-blow was the major contributory factor. Other sources, such as those due to track irregularities, rail-joints and the movements of a locomotive, lateral and vertical, on its springs although of sufficient importance to be taken into account were not of the same order of magnitude. So far had the practice of railway engineering departed from the 'systems' concept that, despite the international work and the publications referred to earlier, these findings were a cause of surprise. And when in 1929, Gribble told the Institution of Civil Engineers that '...the hammer-blow of engines is a factor novel to many bridge-engineers,'[68] it seems to indicate that they were satisfied with working to rule-of-thumb 'static axle load' criteria rather than that they were unaware of the potential problems arising from hammer-blow. Indeed, an engineer would have led a very introspective, insular professional life not to have been at least conscious of a topic which had merited regular mention during the preceding thirty years. The absence of calamities or even of serious trouble, due to lack of provision for impact loading in bridges probably convinced those involved in the business that sound and sensible codes of practice were already in existence and could be used with confidence. Since they were not professionally concerned with locomotives the need or the desirability for a rational design procedure to match the two elements of the railway system into a harmonious working relationship was not perceived. Perception,

when it arrived, was dramatic because it simultaneously resulted in an appreciation of the true nature of the problem, its magnitude and even more startlingly, perhaps, a realisation of the inadequacy of contemporary methods. The state of affairs revealed by the Bridge Stress Committee was no less harrowing for the locomotive engineers. However, before passing on to this topic it is necessary to consider briefly the analytical work which was performed concurrently with the experimental activities.

4c. Mathematical Analysis

An examination of the analytical theory of bridge oscillations is obviously outside the scope of this study but it was an integral and vitally important part of the work of the Committee, carried out largely by Professor C.E. Inglis of Cambridge University, which provided a rationally based series of impact allowances for civil engineers together with corresponding hammer-blow limits for locomotive engineers. In providing common, compatible standards for both a generalised theory was obviously a fundamental prerequisite because as the Report itself stated,

> The determination of Bridge Impact Allowances will attain finality only when it ceases to depend upon empirical rules and becomes founded on a sound analytical basis. This ideal cannot be attained by a mere multiplicity of experiments. Experimental research is necessarily restricted in its application, and

> experimental records, no matter how numerous, fail to achieve their full value until they are shown to be particular cases fitting into a comprehensive theory.[69]

In his paper delivered before the Institution of Civil Engineers Professor Inglis had stressed that for the proper study of such a problem mathematical work and experimental research should cooperate '...until they come into harmonious agreement.'[70] To assist in this he had a model bridge constructed in his laboratory over which he could run an idealised locomotive, which in turn could be adjusted to deliver hammer-blows of predetermined frequencies. Tests with this apparatus, of which Fig.6.9[71] is a record taken from the Report, together with a full-scale test on Newark Dyke Bridge verified a correspondence between theory and experiment sufficient to warrant the use of the general analytical method to predict bridge oscillations sufficiently accurate for practical purposes.

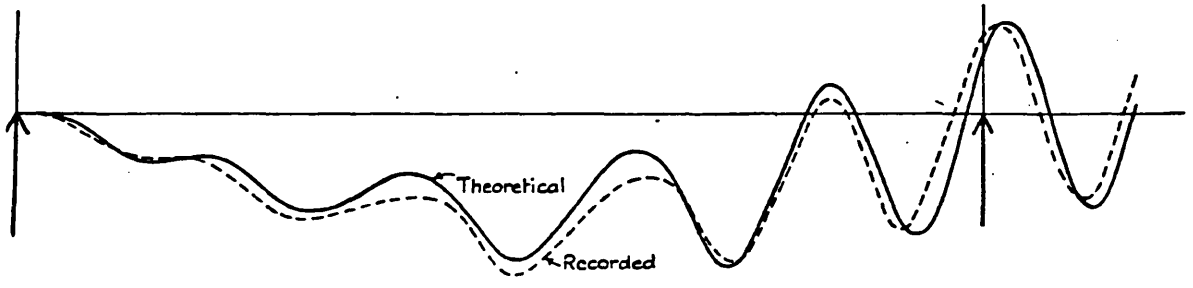


Fig.6.9 Comparison between theory and experiment for model bridge

However, this situation was not persistent and led to further investigations which revealed another interesting facet of locomotive behaviour. In long-span bridges where, as has already been seen, the bridge oscillations were not very great the theory was applicable. But in bridges of intermediate span-length not only was resonance present at the theoretical frequency of the loaded bridge but frequency-amplitude curves indicated the tendency of the amplitude, having peaked and dropped again as the locomotive passed through its critical speed range, to rise again to a second peak. This phenomenon is illustrated by comparing Fig.6.10,[72] which shows the curve for locomotive K on a bridge of 112ft span, with Fig.6.11[73] showing the curve for the same locomotive on a bridge of 262ft 6in span.

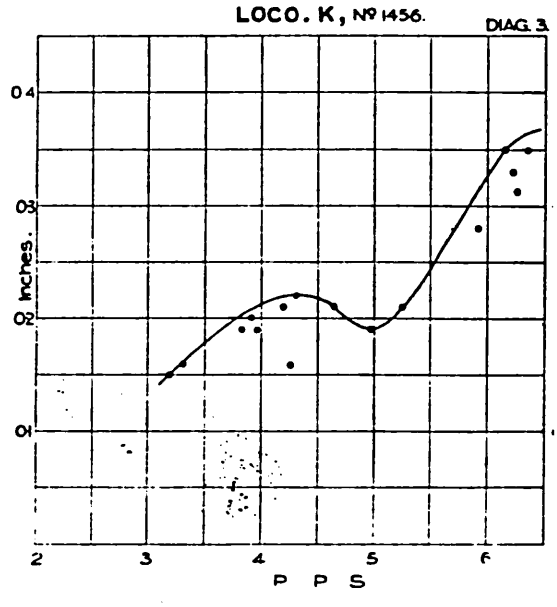


Fig.6.10 Curve illustrating two critical frequencies on a bridge of intermediate span

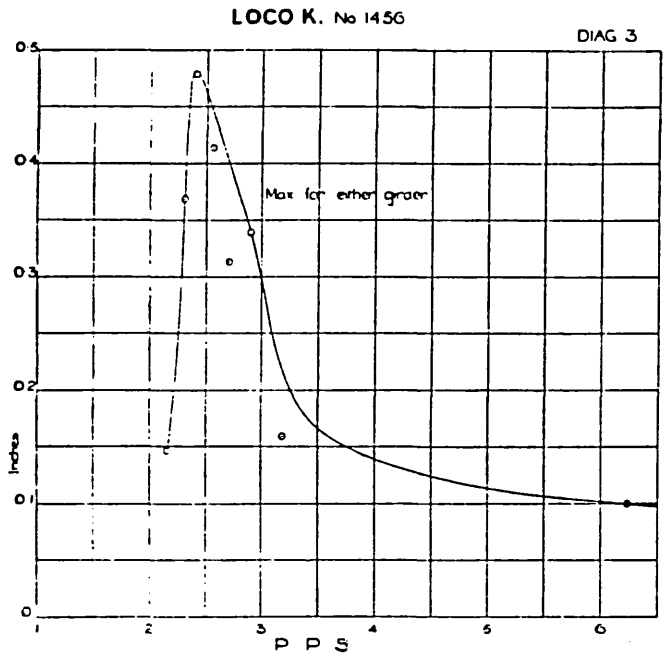


Fig.6.11 Single critical speed on a long-span bridge

This peculiarity was not immediately understood but it was eventually traced to the effects of the locomotive's springs. At the lower speed the frictional resistance within the springs effectively locks them so that the locomotive vibrates almost solidly with the bridge whereas at the higher speed range the springs come into action and only the non-spring-borne parts move solidly with the bridge. In this state, the second or higher critical frequency of the bridge approximates to the natural frequency of the unloaded bridge. In spans where resonance could occur at two frequencies it was

essential to base the impact allowance on the higher frequency because this condition produced the largest hammer-blow.

Under certain conditions, then, it was found that the locomotive suspension was either undamped or underdamped and the fact that the springs could be free at one point in its motion and locked at another point put limitations on 'the application of mathematical analysis to predict every undulation in a bridge deflection record.'[74] However, this was not considered particularly disadvantageous since the object was to predict the maximum amplitude of oscillation. The analysis was based on the idealisation of a stationary locomotive in the centre of a bridge with its wheels slipping at a uniform speed. Originally the model assumed viscous damping[75] in the locomotive springs but this was replaced by a constant damping force which approximated better to observed behaviour. Classification of locomotives by their spring damping characteristics as well as by their hammer-blows was not possible because of lack of information of the former.[76] To allow, with safety, for extreme cases of oscillation, a constant spring damping force of eight tons was adopted to cover both high and low frequency vibrations.[77]

Theoretical curves showing two modes of behaviour of a locomotive on its springs are given in Fig.6.12.[78]

In these diagrams the full lines represent its behaviour when the springs remain locked while the dotted lines indicate the effect of the action of the springs, again clearly illustrating their potential for increasing the dynamic effects of the hammer-blow on spans of intermediate length. This

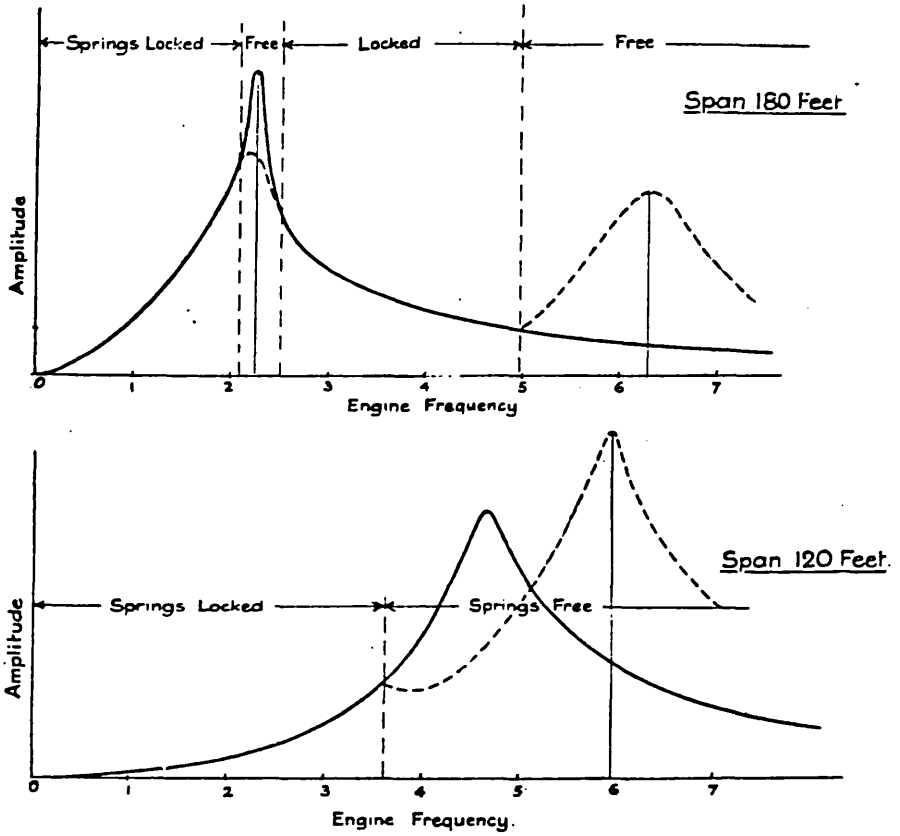


Fig.6.12 Effect of spring movement on amplitude-frequency diagrams

analytical work done by Professor Inglis and its explanation of the seemingly intractable problem given by the perplexing results obtained from the experimental work was judged by Sir Alfred Ewing to be '...the most distinctive contribution to engineering theory which we have been able to make.'[79]

Furthermore, it was of immediate practical use since, as noted above, its reckoning constituted an essential factor in the determination of the appropriate impact allowance.

Thus, the field work carried out by the civil engineers together with the simultaneous analysis was of direct interest to the mechanical engineers because it led to a better understanding of the behaviour of the locomotive as a vehicle

and it also supplied quantitative information on the effects of hammer-blow.

4d. The Locomotives Used in the Tests

The recommendations of the Bridge Stress Committee were not based exclusively on the results of its own tests but also on information supplied by the railway companies at the request of the Committee. To provide the details on balancing sought they had had to measure the hammer-blow of a large number of locomotives chosen from all the principal types.[80] The magnitude of this operation may be appreciated from the reference to this exercise in the words of the Report:

> The individual engines tested are representative of upwards of 9,000 modern engines and include all heavy and important classes of both tender and tank engines.[81]

This job, with the subsequent collation of the results and finally their publication in the Report of the Committee, where they appeared in Appendix D of this document, produced a record unprecedented in the history of locomotive engineering in this country. The hammer-blow characteristics of every important class of locomotive in service throughout the whole country are tabulated. As such, they are evidence of prime importance for this study.

In addition to presenting the raw data which unambiguously reveal the appalling state of affairs existing in

the mid-1920s the Report has an enhanced value for the historian since its contents also largely, albeit in general terms, explain the reasons for the unsatisfactory situation.

For example, while the important locomotive building centres of Crewe, Doncaster and Swindon possessed dynamic balancing machines, the Southern Railway, at Ashford relied on a static balance test only to obtain an approximate check on the correctness of balance weights. At other locomotive centres not only did they not possess a balancing machine at all but generally no checks were made on the state of balance either.[82] This, in itself, of course, is hardly surprising since if the question of balance was treated so lightly that a machine was not provided for the task it is hardly likely that those concerned would go to more troublesome lengths to perform the job. It must also be acknowledged that in the absence of convincing evidence of the ill-effects of excessive hammer-blows on rails or bridges, or the lack of protestation from the civil engineers (hardly likely in view of the traditional lack of communication between the departments), there were no pressures on the locomotive engineers either to make them aware of the consequences of bad practice or to treat the matter more seriously. This stimulus came during the work of the Committee but more dramatically with the publication of its Report.

In summary, of the 174 classes of locomotive either tested or considered by the Committee only one gave no hammer-blow at the reference speed of 6rps. Out of the total 9,309 engines included in the survey, 1,022 exceeded the recommended combined loads whilst of the remaining 8,287

locomotives, 1,575 were identified as improperly balanced in that the hammer-blow of a single axle exceeded that of the whole engine. The following table, Fig.6.13, compiled from data given in Appendix D of the Report, gives the numbers of classes and locomotives exceeding the combined loading recommendations, and those not doing so, belonging to the four railway companies.

	LMS		LNER		GWR		SR	
	No. of		No. of		No. of		No. of	
	Classes	Locos	Classes	Locos	Classes	Locos	Classes	Locos
Exceeding recommended combined loading limit	9	560	11	418	–		4	44
Not exceeding recommended combined loading limit	37	3186	79	3142	16	1376	18	583
Total	46	3746	90	3560	16	1376	22	627

Fig.6.13 Table showing numbers of locomotives exceeding the combined loading recommendations

Based on information from the same source the following table, Fig.6.14, gives a more detailed presentation of the above analysis based on the numbers of two-, three- and four-cylinder engines operated by each company.

	LMS			LNER			GWR			SR		
No. of cylinders	2	3	4	2	3	4	2	3	4	2	3	4
Classes	40	2	4	75	13	2	13	–	3	20	1	1
No. of locomotives	3241	285	220	3153	363	44	1238	–	138	625	1	1

Fig.6.14 Table - analysis based on the numbers of 2-, 3-, and 4-cylinder engines operated by each company

The table below gives details of two-cylinder locomotives which did not exceed the recommended combined loading limit.

	LMS		LNER		GWR		SR	
	No. of		No. of		No. of		No. of	
	Classes	Locos	Classes	Locos	Classes	Locos	Classes	Locos
Hammer-blow on a single axle exceeds that of the whole engine	8	860	10	702	–	–	1	13
Hammer-blow on a single axle being less than that of the whole engine	24	2056	53	2033	13	1238	15	568
Total	32	2916	63	2735	13	1238	16	581

Fig.6.15 Table - analysis of 2-cylinder locomotives

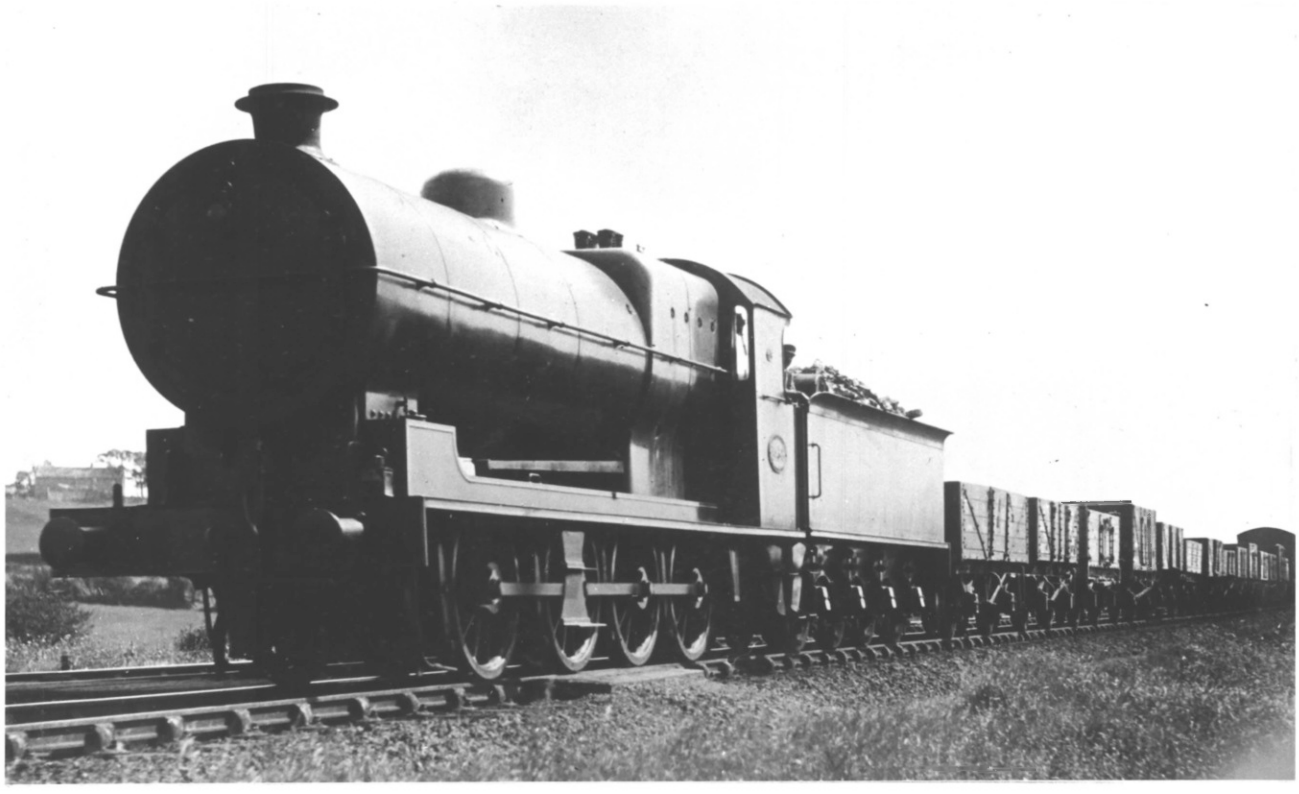


Fig.6.16 Locomotive 'K', Lancashire and Yorkshire Railway, 0-8-0 Engine, No.1438

These figures clearly reveal that in the two largest companies the number of badly balanced engines was significant, although this evidence must be treated with caution because the consequences of this state of affairs were not necessarily serious. The hammer-blow magnitudes quoted in the tables were all calculated at a reference frequency of 6rps.[83] For comparative purposes it was obviously desirable to have a standard and as such the speed of express locomotives was a reasonable choice since the hammer-blow, being directly proportional to the square of the speed, was a maximum under these conditions. And it was these conditions for which the bridge-engineer had to make an adequate impact allowance. However, adoption of this procedure by the Committee did not truly reflect the hammer-blow input to rails and bridges of the slower types of locomotive. The quotation of such figures for speeds that were never going to be attained in normal service, while useful as a basis for comparison, could and apparently in some cases did give a false impression. This is clear from the discussion on Gribble's paper to the Institution of Civil Engineers where contributors obviously responded to Sir Alfred Ewing's comment that with the aid of 'locomotive K' the Committee had been able 'to punish certain bridges as they had perhaps never been punished before', and he told his listeners that

> They had run it at speeds which caused a fluctuation of pressure upon the rails of more than 50 tons in every revolution of the wheels. They had become much attached

to "locomotive K" and hoped it would some day be given honourable burial.[84]

Locomotive 'K' was the designation given by the Committee to two former Lancashire and Yorkshire 0-8-0 engines used extensively in its tests. The photograph, Fig.6.16, of one of them, No.1438, was taken c.1923. They were heavy and powerful engines built in 1903 (No.1438) and 1905 (No.1456) respectively and intended for mineral traffic.

However, instead of interment another participant preferred preservation.[85] Undoubtedly, the machine was regarded as something of a freak by the 'bridge' men and it was left to Sir Henry Fowler, on behalf of the locomotive engineers who were conspicuously absent from the meeting, to inform the audience that an engine designed to haul a load of 1,000 tons at an average speed of 17mph could hardly be expected to behave so well when run at two and a half times its normal speed.

The recently acquired notoriety of the locomotive so incensed Engineering that 'Locomotive K' was accorded the prominence and honour of the first leader in its issue of 22 March 1929. Sympathetically and more graphically it emphasised Fowler's point with the rather acid remark, 'One might as well expect a dignified performance from an old barnyard hen chased by a motor car on the highway.'[86]

In fairness, of course, it must be recognised that the Committee itself acknowledged this fact.[87] Commenting upon four types of LNER engines on which the percentage of reciprocating parts balanced varied from 19 per cent underbalance to 86 per

cent overbalance the Report states

> ...we are informed that no noticeable defects were observed in their running...are slow-running engines in which the effects of unbalanced parts are unlikely to be much in evidence.[88]

Likewise it admitted that some of the engines listed as exceeding the recommended loading limits did so only marginally whilst others coming into this category at the reference frequency (6rps) did not do so at lower frequencies.

Even allowing for the fact that the tabulated data does not provide a completely accurate record in that it gives hammer-blow magnitudes at reference frequency rather than at operating frequencies, it clearly reveals that many locomotives were badly balanced, to the detriment of both themselves and the rails and bridges on which they ran. This unfavourable bias is partially offset, to an unknown extent, by the fact that some locomotives were found to have greater hammer-blows than those listed and consequently were not included in the tables. Of these, some were modified to reduce the hammer-blow while other obsolescent engines were scrapped.

Overall, then, the data obtained from its own experimental work augmented by the information determined and supplied by the railway companies produced a picture of almost unimaginable chaos characterising the state of balancing practice on British railways. Viewed comprehensively, but in terms of individual classes, achievement ranged from virtual

perfection, in the 'Claughton', to unspeakable badness in those omitted from the records. The 'Claughton' class as such was very successful and the ability of the locomotive to haul heavy express passenger trains satisfactorily ensured its growth, by 1917 it numbered 60 locomotives and reached a total of 130 engines in 1923.[89] However, it appears that satisfaction with these smooth-running locomotives was not specifically attributed to their excellent qualities of balance. Contemporary evidence does not suggest that they were regarded as outstanding machines in this respect and it is likely that they were not appreciated, but neither were the bad characteristics of other locomotives. At the other end of the scale the mighty hammer-blow of the George V Class (see Chapter 5. Fig.5.8) did not prevent the engines from acquiring a good reputation. The impressive performance of the first locomotive led to an immediate order for a further nine. In the assessment of O.S. Nock the success of these locomotives was a triumph for Bowen Cooke.[90] How is this situation to be explained? At the expense of a generalisation the answer seems to be that the matter was not taken seriously by those responsible for the design, construction and operation of locomotives.

Design, of course, was ultimately the responsibility of the Chief Mechanical Engineer and traditionally, that is until the time of the Nationalised British Railways' standard steam locomotives, this officer was always credited with an engine appearing during his tenure. In reality he was not necessarily involved in the design process, and even if he was one of those genuinely interested in locomotive design his many duties and

responsibilities almost certainly prevented him from being directly concerned with the various aspects of detail design.[91] With responsibility for building new engines, the repair and day-to-day maintenance of the existing locomotive stud to meet operating requirements, besides similar obligations in respect of carriages, wagons and, indeed, all rolling stock not to mention the accompanying administrative, financial and staffing work the Chief Mechanical Engineer was left with little time to devote to design matters.

The actual design process appears to have been a co-operative task performed by a group, or groups of drawing office personnel, hidden behind a shield of anonymity that defies and defeats the penetrative assaults of the inquisitive student of locomotive design. Within such a milieu and proceeding by entrenched rule-of-thumb methods standards of competence and achievement could and, the evidence indicates, did vary tremendously. Its distinguishing characteristic was often inconsistency. Thus we find, for example, that in 1930 the LMSR produced a 2-6-2T passenger and mixed traffic engine of which E.S. Cox has written '[it was] one of the feeblest locomotives of modern times' and yet 'The same office, but another part, had already produced an entirely excellent 2-6-4 Tank.'[92]

As the preceding chapter has shown standards of balancing practice displayed no more consistency and despite the anecdotal nature of some of the evidence presented there, the Report of the Bridge Stress Committee confirms its general veracity. Indeed, its comments on the balancing of two-cylinder

engines justify the above assertion that it was simply treated in a superficial, routine manner.

> Our observations point to the necessity not only of calculating the position and amounts of balance weights which will eliminate variations of rail pressure so far as may be consistent with other requirements, but also of ensuring that when the engines are constructed the balance weights are in accordance with the calculations. Tests which have been carried out to check the balancing of a number of engines have revealed serious differences between the unbalanced vertical forces as calculated from the drawings and those which are actually produced by the engine.[93]

The emphasis here on the need to calculate both magnitude and position of the balance weights implicitly suggests that the investigations of the Committee had revealed instances where this had not been done. Even where this, the essential design requirement if a dynamically acceptable locomotive was to be constructed, was carried out there is reason to suspect that the calculations were not always correctly performed. Indeed, based on Gresley's remark to Bulleid it seems that in one drawing office the staff were deemed by their chief engineer to be incapable of doing so. And then another factor of practical consequence was the adopted practice within the particular drawing office or for a particular class of engine. Appendix D of the Report reveals

many variations. Some of them undoubtedly originated from conscious design decisions, such as concentrating the whole of the balance weight for the reciprocating masses on the driving axle, and different methods of distributing this balance weight between the coupled axles. Others, such as lack of sufficient balance even for the revolving parts, and balance weights located in an incorrect angular position probably derived from errors, or carelessness, or both.

Added to this chaotic situation was the failure, in many cases, to achieve what was desired. The hammer-blow of locomotives was not checked. In fact some locomotive works did not even possess the equipment to make such a check. And so badly balanced engines in their hundreds were pounding the tracks and bridges with an unnecessary and unwarranted severity. Failure to appreciate the effects of this on both the permanent way and the locomotives themselves, accompanied by a railway management and organisation which separated to the point of complete isolation the civil and mechanical engineering functions led to the situation depicted here.

As this chapter has shown it was the increasing anxiety of the bridge engineers which culminated, in the early 1920s, in direct Government intervention, initially through the Ministry of Transport and almost immediately afterwards, the Department of Scientific and Industrial Research, that led to the quantitative revelation of the dynamic consequences of the locomotive on the way. It presented locomotive designers with a clear, unambiguous, picture of balancing technique as it existed, convincingly demonstrating the deficiencies of routine

methods unthinkingly applied. Further, it gave some positive guidelines and criteria for future use.

It would not be appropriate or relevant here to consider the findings and recommendations of the Committee as they affected the bridge designer apart from noting that they provided him with tables of impact allowances, which included besides hammer-blow, rail-joint and lurching effects.[94]

For the locomotive engineer the main message was clear, the hammer-blow should be kept to the practical minimum, since bridges with spans in the range 100ft to 200ft were particularly vulnerable as a result of resonance. This may be appreciated from Fig.6.17[95] which shows, for a single track bridge, the live load plus impact allowances (including rail-joint effects) expressed as a uniformly distributed load.

The curve marked C, is the enveloping curve for impact effects to be provided for under loading C while that marked A and B shows the greatest impact effects experienced under loadings A and B. The advantage of avoiding the heavy hammer-blow of loading C is conspicuous.

Fig.6.18[96] shows the reduction of impact effects when the locomotive speed is limited to 4.5rps instead of the reference speed of 6rps. This limit and provision was applicable to many branch lines.

In making allowances for impact the Committee adopted the standard of axle loading defined by the British Engineering Standards Association and made recommendations for hammer-blow effects by three loading ranges. These were:

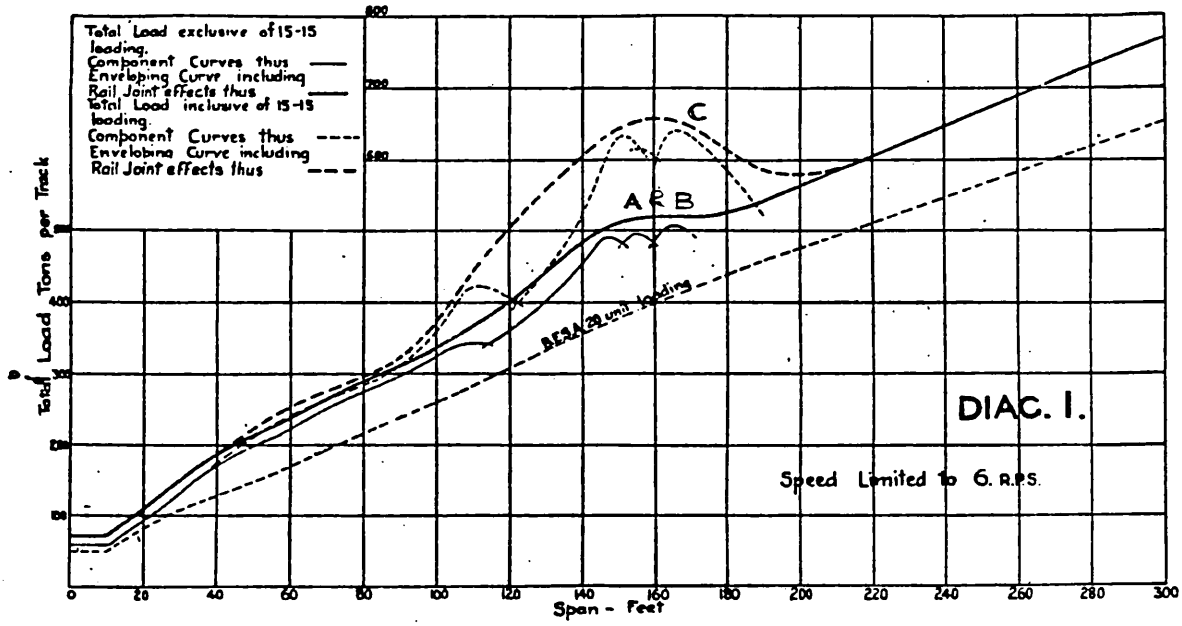


Fig.6.17 Curves for Loads producing Bending Moment - single track bridges

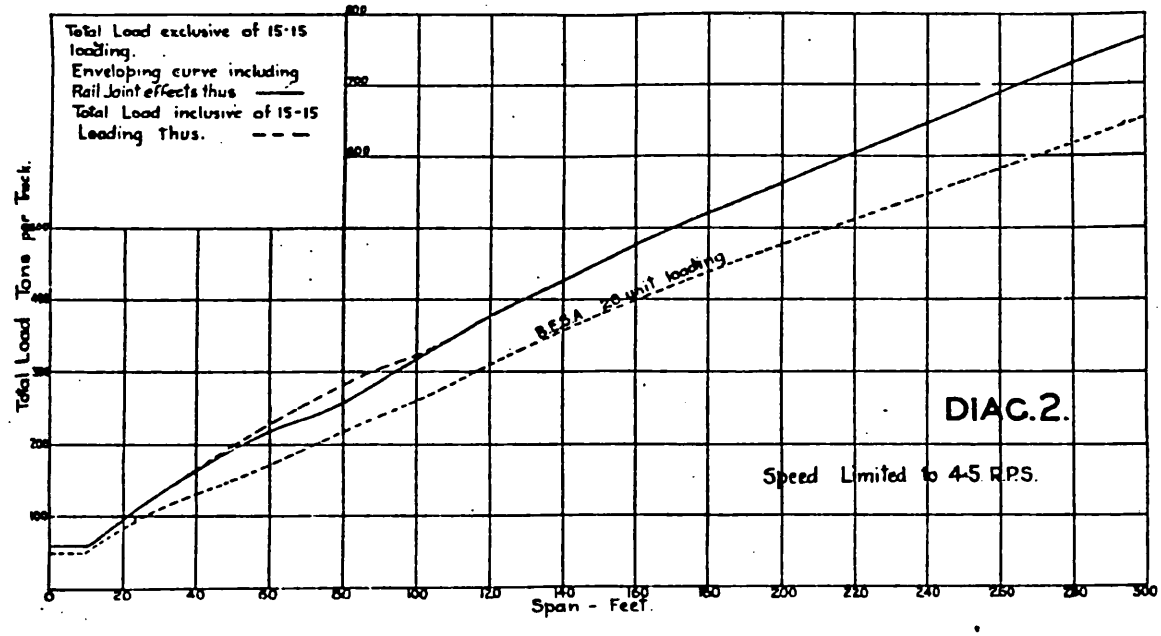


Fig.6.18 Curves for reduced speed

Loading A : 20 units with 5.0 tons hammer-blow (at 5rps)

Loading B : 16 " " 12.5 " " " "

Loading C : 15 " " 15.0 " " " "

Since the report stated that there were not any engines in existence whose weight was represented by 20 units, 18 units being the highest found in practice, some provision was made for future growth. Even so the point was made, based on received information, that future, heavier steam locomotives would have more than two cylinders and that their hammer-blow would not exceed 5 tons at 5rps. As the above table clearly shows, the Committee restricted the heaviest locomotives to the smallest hammer-blow because it assumed that in future the most powerful engines would possess either three or four cylinders and thus afford the opportunity to secure minimum hammer-blow.

Indeed, here we find the first tangible evidence of the fruitful outcome of the cooperation between the major departments of railway engineering, at last recognising the interaction of locomotive and track.

> We are informed by Sir Henry Fowler that the locomotive engineers of the principal railways of this country are prepared to limit the hammer-blow at 5rps on any axle of engines of future design to one-fourth of the normal load on that axle, or to 5 tons as a maximum, and

> further to limit the total hammer-blow of such engines at the same frequency to 12.5 tons.[97]

These parameters were established for two-cylinder engines, the most numerous types in use, which were thus to conform to loading B. Loading A was to cover three- and four-cylinder engines while loading C made provision for comparatively light two-cylinder engines with large hammer-blows.

The words of the Report were, then, a frank admission that the job could be done better than it had been in the past and an undertaking that it would be carried out in a methodical, rational manner. This achievement had taken a century of railway engineering to accomplish and its successful conclusion depended upon a prolonged and expensive investigation involving the willing cooperation of the Government, the four railway companies, universities, and a number of specialists. But the simultaneous prosecution of practical and theoretical work by distinguished engineers and scientists is not sufficient to guarantee that a complex problem can be resolved according to plan. In this particular case both an extension of time and an increase of funding were necessary.[98] The magnitude of the undertaking was such that it demanded resources beyond the power of any one of the groups of participants to supply. Essentially it was a task that required a large-scale cooperative effort; that it received it is almost certainly due to propitious circumstances. In particular the coincidence of Government involvement in railway operation during and in the aftermath of

the First World War, the Grouping of the Railways, and the acute prominence of the problem throughout the railway world.

Unquestionably, the Report made it possible for railway engineering to be put on a more scientific basis regarding the locomotive-track relationship. A quantitative loading scale was promulgated which was commonly applicable to both civil engineers and mechanical engineers. The former were enabled to allow for the dynamic action of locomotives, not as an unknown quantity to be safely provided for by means of a universal empirical formula based upon the bridge span alone, but implicitly on accurate detailed knowledge of hammer-blow magnitudes. Likewise the locomotive engineer, instead of being under a general obligation to 'balance' the machine but with no specific requirements to fulfil, was confronted with the problem of not exceeding precisely defined maxima in terms of both axle loading and 'whole engine' effect. Complying with the two parameters demanded adequate consideration being given to the proper weight to be balanced and also to the method of distributing the balance weight between the axles.

However, what the correct proportion of the reciprocating masses to be balanced was remained a topic untouched by the Committee. The tests conducted had revealed the illogicality of adhering to an arbitrary percentage, such as the popular 66 per cent. This fact was noted and the following observation was made:

> The influence of inertia forces on the engine is affected by the following factors which should be

considered in prescribing the amount of the balance weights:

(a) The number of cylinders and crank arrangements.

(b) The spacing of the cylinders.

(c) The weight of the locomotive.

(d) the length of the locomotive.[99]

and in its General Conclusions as to Balancing it advised

> The proportion of reciprocating parts which is balanced should be limited to what is absolutely necessary to ensure smooth running, and should be distributed between the axles so as to keep the maximum blow per axle and the maximum blow per wheel to the lowest limits.[100]

Professor Dalby, in Appendix C of the Report, stated that this question required further experimental research.[101] Bearing in mind that one of the problems confronting the Committee was

> To investigate the characteristics of locomotives, and the possibility of modifying their design, with a view to reducing impact effects.[102]

it is surprising and somewhat disappointing that the Committee did not enlist a few locomotive engineers to investigate this particular problem. It was the crux of the whole matter. Hammer-blow was generated by the overbalance and its magnitude

was directly proportional to the percentage of the reciprocating masses balanced. To secure optimum benefits from the whole exercise required this very piece of work and yet it was not initiated. The major cause of the trouble the Committee was instituted to deal with, having been clearly identified was not subjected to the rigorous examination of the response of bridges to the locomotive-induced impacts. Thus, as has been seen above, limits of hammer-blow acceptable to the civil engineer were laid down and agreed by the locomotive engineer and, without question, this marked an unprecedented advance on previous practice but the opportunity was not taken to investigate the dynamics of locomotive behaviour. Having indicated that factors such as locomotive weight, length of wheelbase, number and disposition of cylinders all had an influence on the motion of an engine and should be considered, the Committee stopped short of giving guidance on the subject.

Hammer-blow in the conventional steam locomotive arises from the deliberate insertion of balance weights to mitigate the effects of the horizontal disturbing forces. The compromise nature of the exercise was hardly given any emphasis in the Report and in this respect it can be justly claimed that its value to locomotive engineers could have been greater. The tables given in Appendix D, for instance, would have been more informative and interesting if they had included details of the percentage of reciprocating masses balanced and of the horizontal disturbing forces - or data from which these forces could have been determined. Control of the hammer-blow was important, it formed the basis of the loading recommendations,

and yet reduction in its magnitude was at the expense of increasing the other disturbing forces. A study of the interrelationship of these would have been a valuable contribution to the work of the Committee.

In its membership, however, it was not adequately staffed for this task. And within the constraints of time and of finance it probably considered itself unable to embark upon a major investigation of locomotive design. Its main function of providing bridge designers with a rational method of allowing for impact was successfully even if not simply accomplished. In the course of this achievement locomotive engineers had been shown, in dramatic and convincing fashion, the effects of bad balancing - not only on the track and bridges but upon the locomotives themselves. It was an old lesson repeated. A.W. Makinson, who did not subscribe to the very early ideas of the vertical forces expending themselves harmlessly on an unyielding track unequivocally stressed the pertinence of Newton's Third Law of Motion to his audience at the Institution of Civil Engineers in 1863.[103]

And so the work of the Bridge Stress Committee, although incomplete in important aspects of locomotive design, nevertheless raised the subject of balancing to its rightful position of importance and established it on a more rational basis. The rewards for doing so were almost immediate. During the 1930s locomotive design and performance reached their zenith. This was the result of the combination of a number of contributory factors, not least among them being better balancing practice.

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1. Pye, David, The Nature of Design, Studio Vista, London, 1964, p.15

2. Simmons, Jack, The Railway in England and Wales 1830-1914, Leicester University Press, 1978, p.142.

3. Duffy, Michael, 'Rail Stresses, Impact Loading and Steam Locomotive Design', History of Technology, Ninth Annual Volume, Mansell Publishing Limited, London, 1984, p.43.

4. Patent No.3431, Blenkinsop, John, 10 April 1811.

5. Four of Blenkinsop's gear-driven locomotives were built and they were in revenue earning service for over twenty years.

6. (i) Simmons, J., op.cit., pp.142-151.

   (ii) Morgan, Bryan, Civil Engineering: Railways, Longman, London, 1971.

   (iii) Allen, Cecil H., Modern British Permanent Way, The Railway News, London, 1915. This includes a history of the development of the modern bull-headed steel rail.

7. Adams, William Bridges, English Pleasure Carriages, Charles Knight & Co., London, 1837, p.303. He claims that the necessary characteristic of a railroad is 'a continuous equable surface' and admits 'if this surface

can be made perfectly solid and unchangeable, it may answer' but then more practically concluding '...in default of this, it is absolutely necessary that it should possess the quality of vibration.'

8. Makinson, A.W., 'On some of the Internal Disturbing Forces of Locomotive Engines', Proceedings of the Institution of Civil Engineers, Vol.22, 1862-63, p.65.

9. (i) Fox, Francis, 'On the Results of Trials of Varieties of Iron Permanent Way', Proceedings of the Institution of Civil Engineers, Vol.20, 1860-61, pp.259-291.

   (ii) Brunlees, James, 'Railway Accidents - their causes and means of prevention', Proceedings of the Institution of Civil Engineers, Vol.21, 1862, pp.345-424.

   (iii) Williams, R. Price, 'On the Maintenance and Renewal of Permanent Way', Proceedings of the Institution of Civil Engineers, Vol.25, 1865-66, pp.353-428.

10. Fox, Francis, op.cit., p.290.

11. Brunlees, J., op.cit., p.346.

12. Williams, R. Price, op.cit., pp.380-381.

13. Ibid., p.403.

14. Ibid., p.409.

15. Booth, W.H., 'Hammer-Blow in Locomotives', Journal of the Franklin Institute, Vol.CXXIII, No.1, January 1887, pp.42-47.

16. Schivelbusch, W., The Railway Journey. Trains and Travel in the 19th Century, Basil Blackwell, Oxford, 1980, p.127.

17. Rankine, W.J.M., 'On the causes of the unexpected breakage of the Journals of Railway Axles; and on the means of preventing such accidents by observing the Law of Continuity in their construction', Proceedings of the Institution of Civil Engineers, Vol.2, 1843, pp.105-108.

18. Braithwaite, F., 'On the Fatigue and Consequent Fracture of Metals', Proceedings of the Institution of Civil Engineers, Vol.XIII, 1854, p.463.

19. McConnell, J.E., 'On Railway Axles', Proceedings of the Institution of Mechanical Engineers, 1847-1849, pp.13-27.

20. Timoshenko, S.P., History of Strength of Materials, McGraw-Hill, New York, 1953, pp.162-173.

21. Department of Scientific and Industrial Research (DSIR), Report of the Bridge Stress Committee, HMSO, London, 1928, p.8. The Report dismisses the notion that provision should be made for possible fatigue: 'There is no reason to suppose that fatigue becomes operative under the conditions of stress which actually apply in bridges; and there appears to be no experience of failures in steel or wrought iron bridges traceable to this cause.'

22. The particular concern at this period was caused by recent trends of growth in both the weight and speed of

locomotives. Essentially the problem had occupied the minds of bridge engineers from the beginning of the railway era and it was given impetus by the failure of Robert Stephenson's girder bridge over the river Dee at Chester in 1847. Following this accident an investigation of the behaviour of beams under the action of moving loads was conducted at Portsmouth dockyard. For further details on this topic see Timoshenko, ref.20.

23. Melan, J., 'On the Dynamic Action of Rolling-Loads on Iron Bridges', Proceedings of the Institution of Civil Engineers, Vol.117, 1894, pp.411-412.

24. Farr, William Bean, 'Moving Loads on Railway Underbridges', Proceedings of the Institution of Civil Engineers, Vol.141, 1899-1900, pp.2-106.

25. Cookson, A.C., 'The Strength of Railway Bridges', Engineering, 8 September 1922, p.293. The point is made by this engineer that the early engineers had made an allowance for 'impact' and that it was included in the maximum working stress adopted, i.e. 5 tons per square inch.

26. Farr, William Bean, op.cit., p.6.

27. DSIR, op.cit., p.5.

28. This formula, due to C.C. Schneider, had its origin in his investigations into the impact effects of rapidly moving loads on bridge members. It was incorporated into his bridge specification written for the Pencoyd Iron Company in 1887 and thereafter was adopted by the

Government of India, many American railway companies and was included in the 'General Specifications for Railway Bridges' of the American Railway Engineering Association.

29. Identical unit stresses were used for both static and dynamic loads. However, the value used depended upon the user of the Pencoyd formula, for example, the American Bridge Company, with steel, used a stress of 7.5 tonf in^{-2} while the Indian Government Railways used a stress of 8 tonf in^{-2}. See ref.21.

30. Gribble, Conrad, 'Allowance for "Impact" in Bridge Design', Cassier's Engineering Monthly, Vol.XLVIII, 1915, September pp.135-141; October, pp.212-216.

31. DSIR, op.cit, Appendix A, pp.143-145.

32. Ibid., p.144.

33. The Railway Gazette, 12 August 1921, p.278.

34. Lomonossoff, George V., Introduction to Railway Mechanics, Oxford University Press, London, 1933, p.169.

35. Anderson, Charles William, 'On Impact Coefficients for Railway Girders', Proceedings of the Institution of Civil Engineers, Vol.CC, 1914-1915, pp.178-286.

36. Farr, William Bean, op.cit., p.4.

37. The Railway Gazette, Vol.50, 1 February 1929, p.158.

38. Ministry of Transport (MOT), Tests of Railway Bridges in Respect of Impact Effect, HMSO, London, 1921. Report of Major A. Mount, RE, Inspecting Officer of Railways.

39. Ibid., p.2

40. Ibid., p.4.

41. Ibid., pp.6 and 7.

42.,43. Ibid., Diagrams are located between Sheet No.12 and Sheet No.13 of the Report.

44. Ibid., p.5.

45. The GWR 'L' Class 2-6-2T engine used in the experiments was stated, in the Report to have a total weight in working order of 78 tons and 16 cwt. The same Company's 4-cylinder 4-6-0 tender engine, 4046 Class, had a total weight in working order of 75 tons 12 cwt.

46. The formula given here,

$$I = \frac{120}{90 + \left(\frac{n+1}{2}\right)L}$$

covers bridges with more than one track. 'n' refers to the number of tracks and in the case of a bridge carrying a single track the formula obviously reduces to the form given in Major A. Mount's Report.

47. MOT, op.cit., p.7 and also Appendix III.

48. DSIR, op.cit., p.6.

49. The Railway Gazette, 12 August 1921, p.278.

50. Members of the Bridge Stress Committee appointed in March 1923: Sir J. Alfred Ewing (Chairman), Mr C.J. Brown (LNER), Mr A.C. Cookson (GWR), Professor W.E. Dalby, Mr G. Ellson (SR), Sir Robert R. Gales, Professor C.E. Inglis, Colonel Sir John W. Pringle, Mr R.V. Southwell, Mr E.F.C. Trench, (LMSR). As listed in the Report of the Committee p.7.

51. DSIR, op.cit., p.111.

52. Ibid., p.7.

53. Gribble, Conrad, 'Impact in Railway Bridges, with Particular Reference to the Report of the Bridge Stress Committee', Proceedings of the Institution of Civil Engineers, Vol.228, 1928-29, pp.46-79.

54. Ibid., p.47.

55. Sir Henry's lack of interest in locomotive design is attested by:

    (i) Cox, E.S., Locomotive Panorama, Vol.1, Ian Allan, London, 1965, pp.48-49, 60.

    (ii) Marshall, John, A Biographical Dictionary of Railway Engineers, p.85.

56. DSIR, op.cit., p.10.

57. Gribble, Conrad, op.cit.

58. DSIR, op.cit., p.5.

59. Ibid., p.7

60. Ibid., p.12.

61. Ibid., Appendix B of the Report gives details and drawings of the bridges tested.

62. Ibid., Fig.16.

63. Ibid., Fig.35.

64. Ibid., Fig.1.

65. Ibid., Appendix H of the Report describes the Bridge Oscillator and other Special Apparatus (pp.199-200).

66. Ibid., p.18.

67. Ibid., Fig.19.

68. Gribble, Conrad, op.cit., p.51.

69. DSIR, op.cit., p.89.

70. Inglis, C.E., 'Theory of Transverse Oscillations in Girders, and its Relation to Live-Load and Impact Allowances', Proceedings of the Institution of Civil Engineers, Vol.218, 1923-24, Pt.II, p.225.

71. DSIR, op.cit., p.97, Fig.49.

72. Ibid., p.51.

73. Ibid., p.47.

74. Ibid., p.99.

75. Viscous damping postulates a damping force which is proportional to displacement from an equilibrium position.

76. The springing of locomotives, the relative advantages of coil springs and laminated springs, suspension designs, etc. were topics pertinent to the vehicular behaviour of locomotives on bridges but not considered in detail by the Bridge Stress Committee.

77. DSIR, op.cit., p.100.

78. Ibid., p.97.

79. Ewing, Sir J. Alfred, 'The Vibrations of Railway Bridges: An Example of Co-operative Research', Journal of the Royal Society of Arts, Vol.LXXVII, 3 May 1929, p.641.

80. According to the Report of the Committee (p.169), the railway companies 'experimentally checked the hammer-blows...' of locomotives. This was done either on a balancing machine or statically, this latter method being less satisfactory since it yields the overall

effect of two wheels on an axle rather than the unbalanced force on each individual wheel. Further details on this topic are to be found on pp.13 and 166 of the Report.

81. DSIR, op.cit., p.169.

82. Ibid., p.12.

83. Although a reference speed of 5rps was used to express the hammer-blow of locomotives examined for the Committee, the tables given in Appendix D of the Report quote the hammer-blow calculated at a frequency of 6rps. This speed, 'being the maximum frequency for which it is now proposed to calculate impact allowances...' (Report p.169) '...a condition which is approached in express running' (Report, p.4).

84. Gribble, Conrad, op.cit., p.82.

85. Ibid., p.106. Comment of Mr J.S. Wilson.

86. Engineering, 22 March 1929, p.363.

87. On the subject of speed the Report stated 'The maximum speeds asked for and attained during these tests were often extremely high. With the mineral engines they were very much greater than are ever attained by these engines in ordinary working.' Specifically referring to locomotive 'K' it continued, '[it] has in very many of the trials travelled at over 60mph...' (Report, p.39).

88. DSIR, op.cit., p.171.

89. Nock, O.S., British Locomotives of the 20th Century, Vol.1, Patrick Stephens Ltd., Cambridge, 1983, p.158.

90. Ibid., p.45.

91. Johnson, John and Long, Robert A., British Railways Engineering 1948-80, Mechanical Engineering Publications Ltd., London, 1981, p.120. Also see Ref.55. E.J.H. Lemon, who succeeded Sir Henry Fowler as CME, had been the Carriage and Wagon Superintendent of the LMS and, 'Of locomotives he was largely ignorant', Cox, E.S., op.cit., p.77. Similarly, C.B. Collett, who succeeded G.J. Churchward, '...was primarily a workshop man, and his main interests proved to lie in the improving of constructional techniques, and the incorporation in existing designs of details likely to reduce the maintenance costs of locomotives', Nock, O.S., op.cit, p.233.

92. Cox, E.S., op.cit., p.66.

93. DSIR, op.cit., p.13.

94. Ibid., pp.133-138.

95. Ibid., Fig.75, Diagram 1.

96. Ibid., Fig.75, Diagram 2.

97. Ibid., pp.114-115.

98. Ibid., p.7.

99. Ibid., p.171.

100. Ibid., p.172.

101. Ibid., p.168.

102. Ibid., p.9.

103. Makinson, A.W., op.cit., p.66.

Chapter 7

TO THE END OF STEAM

1. The Aftermath of the Bridge Stress Committee Report

Modifications to the balancing of the GWR, four-cylinder, 4.6.0, 'Star' class locomotives and also to the same company's two-cylinder, 4-6-0, 'Saint' class engines produced improvements in the hammer-blow characteristics of these classes while the Bridge Stress Committee was still in the midst of its labours.[1] Thus it is no exaggeration to claim that benefits deriving from its work were immediate. By the time the Report of the Committee was published all of this Company's locomotives complied with the recommended loading limits and of the four Grouped Companies, details of whose locomotives were tabulated in Appendix D of the Report, it was the only one with no engines 'above the line'.[2]

Modification and scrapping obsolescent engines secured improvement in the dynamic behaviour of existing locomotive stock. These natural processes, long-established characteristics of locomotive engineering, were given impetus by the Grouping of 1923. This major change in the organisation of the country's railway system brought to three of the four new companies that is, the LMS, the LNER and the SR, an inheritance of locomotives both numerous and diverse in types.[3] Rationalisation demanded a reduction of numbers and types and provided the opportunity for a degree of standardisation and economy as replacement occurred over the ensuing years. It was not, however, a sudden change but a gradual transition over a

period of ten years or more.[4] The evidence does not indicate that locomotives were scrapped simply because they were badly balanced but the revelation of this state of affairs in combination with other factors probably hastened the process. Locomotives 'K', the two engines of this designation used in the tests conducted by the Bridge Stress Committee, were early victims, both being broken up in 1928.[5] By this date, however, they were getting on for thirty years old and were thus approaching the end of a normal working life. Additionally, and perhaps more significantly, the Grouping had brought them into direct competition with other locomotives, a situation which clearly demonstrated that the former Lancashire and Yorkshire Railway locomotives were no match for their LMS counterparts. Grouping did not promote a conscious effort to adopt a uniform approach to locomotive practice on a national scale, it merely provided scope for this on a regional as opposed to an individual company basis and the results reflected the interpretations of requirements by the four Chief Mechanical Engineers. Some of these have been referred to in Chapter 5. But such differences did not prevent a more rational approach to the balancing problem which, from origins in the 1920s, was dealt with successfully during the 1930s.

In 1923, confronted with the task of providing a locomotive capable of hauling a 500-ton train at an average speed of 55 mph, R.E.L. Maunsell, on the Southern Railway, initiated investigations to meet this requirement while, at the same time, complying with the weight restrictions of the Civil Engineer.[6] The question of balancing was thoroughly examined

and following trials with a modified Drummond four-cylinder, 4-6-0 engine, in which the cranks were set at an angle of 135° giving eight exhausts per revolution (producing a softer blast but a more even turning moment), this arrangement was adopted for the new locomotive - the 'Lord Nelson', Fig.7.1. When completed at Eastleigh Works in August 1926 this engine had the distinction of possessing the highest nominal tractive effort of any British passenger express locomotive. The engine is significant in the history of British locomotive development because it illustrates that by careful, ingenious design and construction it was possible to achieve a marked increase in the power of the 4-6-0 type with a minimum increase in weight. By the use of high tensile steel for revolving and reciprocating parts it was possible to reduce the balance weights in the wheels and hence the hammer-blow; the maximum on any wheel being only 1.51 tons.[7] Conformity to overall weight limitation was also assisted by manufacturing refinements such as the machining of components normally left as forged or cast. The great care taken over the design of this locomotive included the submission of the balancing calculation results to Professor Dalby for his confirmation.[8] In another important respect the balancing arrangements for the 'Lord Nelson' signalled the beginning of a new phase in extending good practice by providing a model for the study of locomotive engineers. Comprehensive details of the balancing design, instead of being hidden in a design office or printed in the rather inaccessible transactions of a professional institution, were published in the pages of The Engineer.[9]

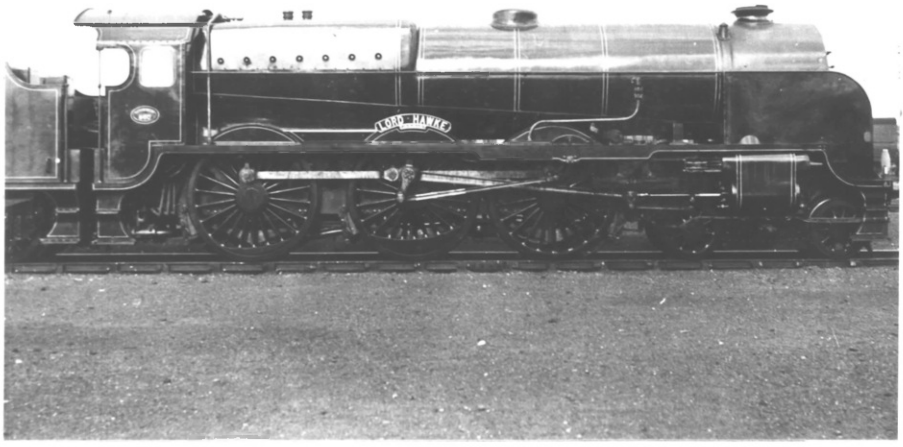


Fig.7.1 'Lord Hawke', Southern Railway 'Lord Nelson' Class locomotive, 1929

The Report of the Bridge Stress Committee set an example too, because it presented in diagrammatic form the hammer-blow characteristics of the locomotives used in its tests. Thereafter, 'Hammer-blow Diagrams' were widely used for summarising information on locomotive wheel-loading.

A realisation that improvement could be secured by giving proper attention to the subject at the design stage led to the adoption of methodical procedures for carrying out the necessary calculations and presenting the results. Appendix 3 shows the document produced for this purpose by the Locomotive Drawing Office of the LMSR, at Crewe.[10] The three-part structure of this specification, consisting of detailed instructions together with relevant formulae, a completely solved illustrative example, and a typical hammer-blow diagram, and the requirement that calculations should be recorded and laid out in a certain prescribed manner was conducive to the subject being dealt with in a logical and uniform fashion. The value of a hammer-blow diagram (such as that given on p.21 of Appendix 3, for example) to both civil and mechanical engineers is obvious, and as will be seen from this Appendix the production of a 'Hammer-blow Diagram' became an integral part of the drawing office procedure on the LMSR.

Experiments with some of Maunsell's two-cylinder 'King Arthur' class locomotives, originally built in 1925, in which the overbalance was reduced to 30 per cent proved successful and when in 1930 he produced his three-cylinder 'Schools' class it, too, had only 30 per cent of its reciprocating masses balanced. Subsequent alterations to some of these engines removed the

overbalance completely and their satisfactory performance in this unbalanced condition is thought to have given O.V.S. Bulleid justification for omitting reciprocating balance entirely from his three-cylinder 'Merchant Navy' class in 1941.[11] Not that this was a new idea at that time. In Appendix C of the Bridge Stress Committee's report, Professor Dalby had indicated the conditions for self-balance of the reciprocating masses although noting the existence of an unbalanced horizontal couple.[12] Likewise, H.A.F. Campbell, simultaneously noted the lack of need to balance reciprocating components.[13]

The reduction in the percentage of reciprocating parts balanced, so long overdue, was well-established by the mid-1930s and the trend was even more marked in Europe where balancing rules restricting the magnitude of the hammer-blow - e.g. maximum hammer-blow 15 per cent of static axle load - limited the percentage of reciprocating masses balanced to low values, often to the range of ten to twenty per cent.[14] In this country the diminution did not go so far and in general it was about 40% on larger engines and 50% on the smaller types but, nevertheless, compared with the old, almost universal, rule-of-thumb 66% these were significant reductions and constituted a great advance on earlier practice. Progressive growth in the power, size and weight of locomotives had reduced the effects of inertia forces generated by reciprocating masses on their motion. Limitations of the structure gauge effectively confined growth in physical dimensions to an increase of vehicle length, the beneficial effects of which had already been discovered and exploited, during the first half of the

nineteenth century, by the expedient of rigidly coupling the tender to the engine. So, too, the upward trend of steam working pressures had a direct, if incidental, contribution to ameliorating the balancing problem. A higher pressure permitted a smaller piston which resulted in a decrease in the reciprocating mass with yet another concomitant bonus because the smaller cylinders enabled their centres to be located closer to the longitudinal axis of the engine thereby reducing the horizontal nosing couple. There is no suggestion here, of course, that steam pressures were consciously chosen to assist with the dynamical problems of locomotive design. And in any case, the move to higher pressures was hardly a simultaneous move on the part of railway companies. For example, Gresley's tardiness and caution in adopting GWR standards here, following the exchange trials of 1925, is a well-known fact of locomotive history. Nor was this delay, of itself, perverse. High-pressure steam only possessed merit if it could be utilized efficiently, which in turn depended largely on the valve gear employed. Again the lag of the LNER on the GWR is part of the same story. Indeed, the whole history of locomotive engineering is complicated by the fact that the engineers involved did not have an objective standard to which to aspire and their success, or lack of it, is not necessarily to be measured in a quantitative manner by comparison with either the personalities or the products of their contemporaries but by their own satisfaction, or that of their superiors, with their achievement. Thus, if an engineer fulfilled his aim of producing an engine that was cheaper, more simple to construct, easier to maintain, in

possession of greater haulage capacity, faster, more efficient in terms of coal consumption, and so on than its predecessor then he, and probably his board of directors, were pleased with the result. Rather than being peculiar to the railway system, however, this situation is still a characteristic of manufacturing industry. Through a wide range of products, from domestic appliances to motor cars and even aircraft, manufacturing companies offer their own 'state of the art' products to potential customers at appropriate levels, from the small shop to large national and even international exhibitions and trade fairs. Although the differences between products are smaller today due to the effects of standardisation and the complex structure of fewer, but bigger companies, the principle nevertheless persists. Success was thus measured by improvement upon an existing machine and as such the whole process of design, construction and operation could be carried on by a company with almost a total disregard for what was being done elsewhere.

Unsought as were the advantages of higher pressures to the balancing of locomotives they were nevertheless tangible.

A further reduction in the mass of the reciprocating parts was made possible from the 1920s by the replacement of plain carbon steels by alloy steels. The development of alloy steels, which I have discussed elsewhere, was prosecuted with vigour during the early years of this century and these metallurgical advances added another term to the series of ferrous materials available to engineers.[15] The sequence, cast iron, wrought iron, plain carbon steels, alloy steels

successively put at the disposal of engineers constructional



Fig.7.2 Great Northern Railway, H.N. Gresley's three-cylinder, 2-6-0, '1000' Class Locomotive, 1920

metals of enhanced physical properties, in particular increased tensile strength. Potentially, this offered locomotive engineers significant opportunities in design and their response was unhesitant. In 1920, Gresley's three-cylinder, 2-6-0, No.1000 class appeared in which, probably for the first time in this country, all the motion rods were of alloy steel, Fig.7.2. The substitution of nickel-chrome steel for the usual carbon steel effected a saving in weight of 51 per cent on the outside connecting rods and 33 per cent on the coupling rods.[16] Not since the introduction of John Ramsbottom's pistons in the 1850s had a comparable reduction in the weight of motion parts been possible. Although conscious attempts had been made to reduce this weight by design. Thus Gresley's design for piston and rod in the form of a single forging (of nickel steel) had antecedents in the efforts of Hackworth and McConnell, in the middle years of the nineteenth century, to produce a combination of these two elements as one component.

Once the attention of British engineers had been drawn to the importance of proper balancing and even more importantly, once they had been given some clearly defined design parameters, they had no great difficulties in meeting requirements. It is probable that standards would have improved earlier if, instead of complying with the old 'two-thirds' rule which demanded little more than a routine, unthinking response to the problem, they had had to design to a weight-limitation rule of the type used in America. The relevant rule of the American Railway Master Mechanics' Association, published in 1915, required the weight of the reciprocating parts on one side of the engine to

be restricted to 1/160 of the total weight of the locomotive, and gave as an ideal the limitation of these parts to only 1/200 of the total weight of the locomotive.[17] Such a rule had the inherent advantage that in relating the mass of the motion parts to that of the locomotive it also related the inertia forces and ultimately the degree of overbalance to the mass of the vehicle. This implicit relationship was obviously absent from the British practice which was based solely on the mass of the reciprocating components. Conforming to the American standard obviously demanded from the engineer a far more detailed consideration of the type of piston, crosshead and other components used together with a most careful and conscious design effort to provide the requisite strength and rigidity with the minimum weight. American practice, however, was not conspicuously better than that of British engineers because the American Railway Master Mechanics' Association rules of 1915 specifically discounted the need for cross-balancing. In principle this was an erroneous decision which led in due course, that is in the 1930s, to troubles when running speeds rose and compelled American operators to adopt the long-established European practice.

Nevertheless, as stated above, given quantitative information on maximum permissible hammer-blow effects and loading figures the locomotive engineers in general provided well-balanced machines which contributed to the high level of design and performance achieved during the 1930s.

Coincidental with the rationalisation of balancing procedures which characterised the period following the work of

the Bridge Stress Committee steam locomotive design generally proceeded on a more scientific basis. It is not the place here to attempt even a résumé of this extensive subject which can be studied in the writings of Ahrons,[18] Cox, [19] Nock,[20] and Reed[21] although the happenings of the decade are germane to the history of locomotive balancing. Besides good vehicular behaviour at high speeds, the outstanding successes of this period are attributable to the engineering achievements in the thermodynamic aspects of steam locomotives, that is, steam generation and steam utilisation. The history of the steam locomotive is replete with examples of boilers too big or too small, likewise cylinders, constricted live and exhaust steam circuits, incompatibility between valves and cylinders and so on. In all the constituent elements of the locomotive, both mechanical and thermodynamic, there had been over the years undoubted improvement but the successful engine was more than the sum of its individual components, it demanded the correct relationship between them. Optimum efficient performance required proper firing rates, with a grate area matched to boiler in turn matched to cylinders, valves, steam circuits, etc. in a harmonious operational combination. And it was the 1930s when this was generally achieved not only in Britain but throughout the world. This high noon of steam traction was described by Cox,

> Performance and efficiency approached the highest level attainable within the Stephensonian conception. What had once been possible only by special effort on special

> occasions, with selected fuel, became general, despite economic and staff problems which were already beginning to bear heavily upon this form of motive power. From this time forward, until the completion of the last steam engine in 1960, no better running performances were achieved and little more power was won for each B.T.U. of calorific value in the fuel. Only mechanical improvements towards reduced maintenance cost continued to progress, some of which were left unfinished at the end of the day, before other forms of motive power took over.[22]

As a result of these technical advances, organisational changes in the post-Grouping period and also to some extent in the fact of increasing competition from the rapidly expanding road transport services, although the severity of this was not so great on long-distance main line routes as on shorter cross-country journeys, high-speed running made considerable progress during this period. Sixty-six new express services, with average overall speeds of 60mph or more, were introduced by the LMSR during the 1930s, while on the LNER the number of express trains averaging these speeds, four in 1914 and twenty-five in 1934 had risen to 107 in 1938,[23] the year in which this company's streamlined Pacific 'Mallard' attained the world's steam locomotive speed record of 126mph, the corresponding rotational speed of the driving wheels being 8.8rps. Obviously the time had arrived when the maximum operational wheel speed of 5rps envisaged by the Bridge Stress

Committee had been surpassed in one or two cases, and was clearly capable of being so in normal service. These circumstances in which actual wheel lift could occur demanded, and received, the attention of engineers.

However, before pursuing this, it is worthwhile to back-track a little to survey briefly other consequences of the endeavours and the Report of the Bridge Stress Committee. This document proved to be a seminal work of value abroad as well as at home. In India it was taken as the basis for further work on the North Western Railway; a description of this work was given in a paper to the Institution of Civil Engineers by W.E. Gelson.[24] In speaking of the locomotives selected for test the author commented, '...of those which had been brought into use before 1928 little or no information was available regarding the balancing'.[25] As a statement it merely accords with what has been written earlier and as such it is not unusual. Nevertheless, as another piece of historical evidence it does support the present thesis that despite the continuous lip-service to the need for balanced locomotives from the middle of the last century the matter was not given the proper attention it merited until well into the present century.

R.W. Foxlee and E.H. Greet also adapted the Report to provide colonial bridge designers with formulae to cope with the different circumstances pertaining in the colonies.[26] Loadings and bridge characteristics generally differed markedly from British practice; for a given span, colonial bridges tended to have a lower mass and a higher natural frequency. The value of the Report was enhanced by the inclusion of Appendix J, in which

Professor Inglis provided details of his analytical processes thus enabling engineers to apply the theory to conditions outside the range of those covered by the Committee in its investigations. Theoretical investigations were continued by Inglis with the object of making the results of the Bridge Stress Committee Report more amenable to drawing office utilisation by the provision of 'concise formulas' and this work led to the presentation of another paper to the Institution of Civil Engineers[27] and, in 1934, the publication of his book A Mathematical Treatise on Vibrations in Railway Bridges.[28] This major work based on beam theory and harmonic analysis amplified his earlier work.

> ...the ground has been more thoroughly explored and the trail has been followed until definite formulae emerge, which are as simple as can be expected, in view of the numerous characteristics which insist on being taken into account. These formulae, though obtained by methods of approximation, yield results which can hardly be improved upon by the fullest possible system of mathematical analysis, and this is all the more gratifying because the full mathematical treatment, in its turn, is found to predict dynamical effects which are confirmed by experiment in a manner which leaves little to be desired.[29]

It also provided a demonstrably successful paradigm for the solution of a complex technological problem. A methodology

which combined analysis and validifying empiricism was essential. In the absence of one of the elements the value of the other was seriously diminished and, indeed, many of the problems which confronted railway engineers, both civil and mechanical, over the years clearly revealed the inadequacy of reliance upon empirical methods alone. This point was emphasised by the author in his introduction

> Purely empirical formulae...can have no permanent place in the science of engineering; sooner or later they must give way to formulae based upon scientific principles, formulae which bear the hallmark of truth, in that they embody all the separate characteristics which theory, in conjunction with experiment, indicate must be taken into account.

He continued by highlighting the difficulties and dangers of a dependence upon theory alone.

> Without the guidance of experimental results to point the way at every cross-road and to check the validity of analytical prediction, this task would have been quite impossible and, deprived of these experimental sign-posts, any mathematician, no matter how astute he might be, would inevitably lose his way in the labyrinth of side-tracks which confront the traveller in this comparatively unexplored territory.[30]

The abstruse nature and the magnitude of the work undertaken to put bridge design on a rational basis unambiguously revealed the part of analysis in such an undertaking. And in doing so it manifestly denied a popular notion, still not dead, that design was but a process of putting theory into practice. It also provided a clear indication of the type of exercise required in respect of the steam railway locomotive but which was never carried out. During the 1930s, the time when this should have been performed the requisite facilities, in the form of a locomotive testing station, were not available and by the time the Rugby plant was opened the future of steam traction was already in question.

Analysis, then, was perceived to have a vital contribution to make to the understanding of and solution of railway problems. The value of cooperation between academic institutions and the railway industry, initiated and exemplified by the labours of W.F.M. Goss and his colleagues at Purdue in the 1890s and more recently demonstrated by the cooperative efforts of the Bridge Stress Committee, stimulated such activity during this decade. The interaction of locomotive and track was the focus of considerable attention and, at long last, after a century of public railway operation, a truly 'systems' approach to the problems of railway design emerged. After the effects of impact, due to hammer-blow, on bridge structures had been revealed it was natural that its effects on the rails themselves would invite inquiry. And it did.

The fourth edition of Professor Dalby's book The Balancing of Engines, covering the work of the Bridge Stress

Committee, was published in 1929 and at this period, in another paper to the Institution of Civil Engineers, he described the increase in rail stresses due to overbalance.[31] This was commonly 50 per cent and could approach 100 per cent as wheel speeds neared 6rps - a situation which left little margin between the stresses the rail had to endure and the elastic limit of the rail material. Control of hammer-blow was obviously important from the point of view of the track too, especially so because of the contemporary upward trend of operating speeds. The wheel-track contact which featured prominently in Professor George Lomonossoff's book on railway mechanics[32] was the subject of another paper by Professor Inglis[33] and an investigation of the impact loading of rails carried out by R.N. Arnold at the University of Illinois, Urbana. These tests, the subject of a paper[34] read before the Institution of Mechanical Engineers by Arnold in 1937 led to improvements in many aspects of rail technology, from manufacture to maintenance. A detailed consideration of this work has been published by M. Duffy.[35] It is not the main purpose of this study to pursue in detail the civil engineering side of the locomotive-rail relationship. Enough has been written to show that by this time it had become, by general acknowledgement a common problem, to be tackled jointly by working to clearly defined and mutually agreed design parameters. Because of this and as a result of the major reorganisation experienced in the wake of Grouping the old isolation of various departments of railway companies was finally broken down, to the benefit of all concerned. The days

when a civil engineer could reject a locomotive out-of-hand, without reason were happily over by the mid-1930s. However, the technical problems posed in balancing locomotives had achieved a new level of significance by the latter years of this decade.

2. The Final Phase

As a consequence of the improved balancing techniques made possible by the work of the Bridge Stress Committee and the rationalisation of design referred to earlier, not only was better vehicle behaviour and performance an immediate achievement it also provided the potential for even greater speeds. Whereas the recommendations of the Committee made provision for wheel speeds of 5 rps by the end of the 1930s, 8 rps was 'a maximum speed of which most modern designs are capable.'[36]

The dynamic augment, or hammer-blow, which increased in direct proportion to the square of the speed now made further investigation essential. Wheel lift had actually been shown to be possible under laboratory conditions at Purdue and by 1937, also in the United States, evidence of bouncing of the coupled wheels on the track had come to light. Associated with the increased magnitude of these vertical forces was the matter of their horizontal effects on the locomotive itself, an aspect of the balancing problem untouched by the Stress Committee and still largely unexplored. Such considerations were the genesis of a lengthy, comprehensive paper delivered to the Institution of Locomotive Engineers early in 1938.[37] For as D.C. Brown, its author stated in his opening remarks,

> ...although so much has been done to ascertain the effect of hammer-blow on bridges, there has been very little scientific investigation of the disturbing effects which the unbalanced reciprocating masses exert on the locomotives. Hence, although the locomotive engineer is well aware of the maximum balance which can be allowed, he has little data to guide him at the other end of the scale. Such practical test results as are available seem to indicate that in many cases locomotive designers may have been unduly apprehensive of the disturbing effects of the horizontal forces, especially on the heavy locomotives now used.[38]

Following a wide-ranging survey which included details of balancing practice on both British and foreign railways and the various methods used for controlling the hammer-blow the author concluded by recommending that the amount of balance should be regulated by means of two limits. The upper limit, to prevent excessive hammer-blow on the track and bridges, would be determined by mutual agreement between the civil and mechanical engineers. At the other end of the scale, the lower limit defining the minimum unbalanced masses and dependent upon acceptable riding quality and maintenance standards was the sole responsibility of the locomotive engineer. Such limits could be based upon the existing balancing rules discussed in the paper with the details, such as constants, determined by individual railways to meet their specific requirements. This paper, in

which the emphasis was on conditions abroad rather than in Britain, was an appraisal of the 'state of the art' which looked forward to further work more than providing data for immediate use. Its content and its very publication provide unmistakable evidence that with steam traction, on a world-wide scale, at its apogee the problem of locomotive balancing had not reached a definitive solution. The unfinished condition of this integral part of design, and the need for more effort, was clearly perceived and articulated by those most directly involved.

In Britain, by the end of the 1930s conditions had been reached where wheel lift was a possibility and although, according to Cox, no authentic observation of the phenomenon had been made occasional, mysterious, cases of bent rails occurred and an investigation of the matter was entrusted to the Research Department of the London, Midland and Scottish Railway. Tests were conducted with three two-cylinder, 4-6-0, locomotives balanced for 66.6 per cent, 50 per cent and 30 per cent of the reciprocating masses respectively. These were run along a selected length of track, with greased rail heads to promote slipping, at speeds of 10 to 18 mph giving slipping speeds of up to 110 mph which were measured by means of a cine-camera. This also provided a photographic record of the behaviour of the wheels on the rail. Fig.7.3,[39] an example of these photographic records, shows wheel lift at a high rotational speed.

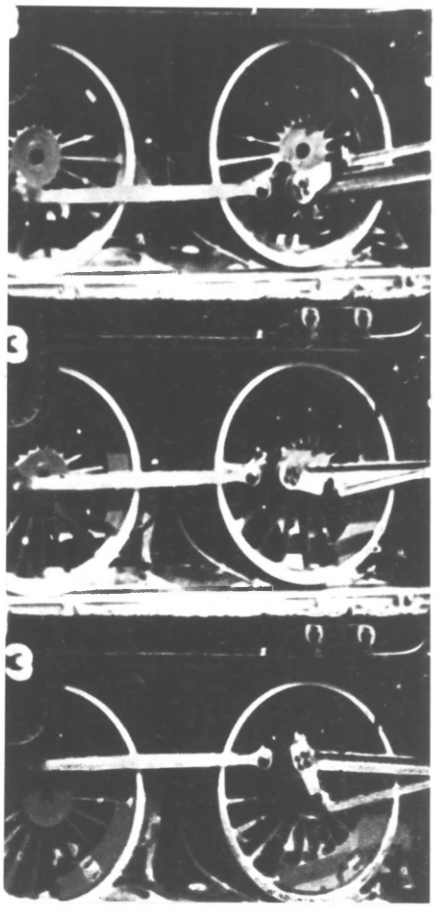


Fig.7.3 Illustrating wheel lift.

These tests revealed a maximum lift of the driving wheel of 2.4 inches on the engine with 66.6 per cent balance at a slipping speed of 103 mph. The locomotive with 50 per cent balance produced a lift of only 0.4 inch at a slipping speed of 104 mph, while that with 30 per cent gave 'no appreciable lift' at 99 mph. However, the corresponding engine oscillations were classified as 'nothing abnormal', 'moderate', and 'excessive', respectively. Thus, as Nollau's experiments had shown almost a hundred years earlier, these tests once again demonstrated the inter-relationship of the horizontal and vertical disturbing

effects and the possibility of reducing one at the expense of increasing the other. At the higher level of speeds involved, though, Cox's paper emphasised the critical nature of the degree of compromise adopted together with indisputable evidence of the dire consequences for the track of balancing too high a percentage of the reciprocating masses. Figs.7.4[40] and 7.5[41] show damage to the track resulting from these tests.

The kinked rail, shown in situ, and the extent of its distortion in the free state illustrated in these photographs do not give a complete indication of the measure of damage to the permanent way, where injury to the ballast caused a persistent settling of the track.



Fig.7.4 Kink in track after slipping tests.

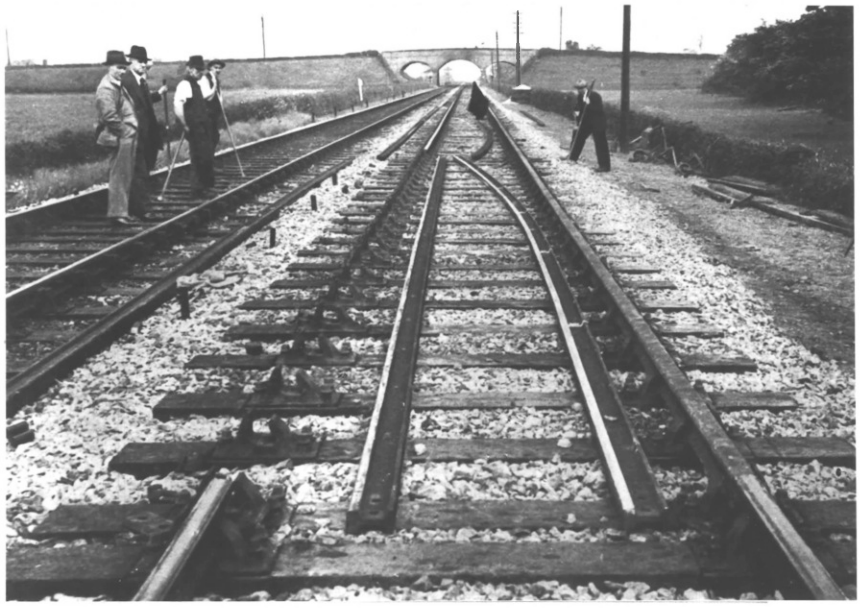


Fig.7.5 Damaged rail after removal.

A number of deductions were made from these tests, including the necessity of reducing hammer-blow to diminish wheel bounce and track damage although the scope for such a reduction was limited by the requirement of controlling longitudinal oscillation of the locomotive. Wheelbounce itself, illustrated in Fig.7.6[42] was generated by the unbalanced forces and was of the nature of a forced vibration rather than resonance between locomotive and track, the state of which had little effect upon the phenomenon.

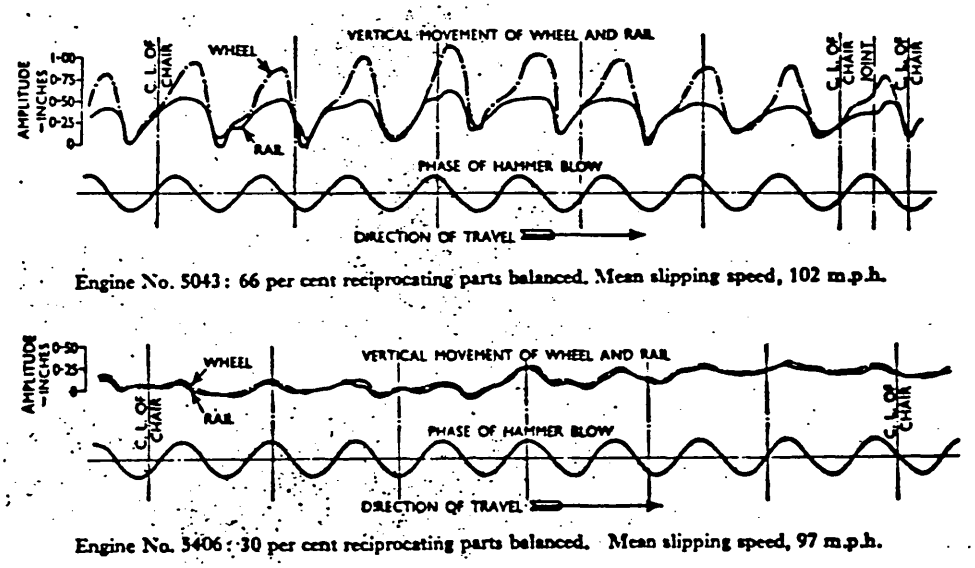


Fig.7.6 Diagram to illustrate Wheel Bouncing.

This particular experimental work marked a great advance on earlier investigations. In the mid-nineteenth century tests with freely suspended locomotives in Germany, France and Britain neglected the track, as did the work at Purdue in the closing years of the century. During the 1920s, first the Ministry of Transport tests and second the work of the Bridge Stress Committee effectively ignored the locomotive, it was merely employed as a track-loading device. And now, at last, virtually at the end of steam locomotive development - not that those involved at the time were aware of this - a serious study of the 'locomotive-track' combination had been undertaken. The benefits of this were twofold.

Irrefutable proof had been given of the potential serious consequences for the permanent way of adopting unduly high overbalance on locomotives. The results of the tests, showing the potentially dangerous wheel lift and damage to the track caused by the hammer-blow due to a high percentage of balance of the reciprocating parts, led to the class of engines used in the tests having its overbalance reduced from 66.6 per cent to 50.0 per cent.

The locomotive itself was also clearly identified as being worthy of a meaningful and thorough investigation. The need to reduce hammer-blow to a minimum even if it could not be eliminated was recognised but the root of the problem was the horizontal disturbing forces which could reach a large magnitude in two-cylinder engines. Cox summarised the current state of the art,

> The effect of these horizontal forces on the locomotive is, however, unlike the hammer-blow effect, very ill-defined. Neither recorded theory nor experiment has so far analysed clearly the resulting oscillations, showing on the one hand how they vary in relation to engine weight, length, and weight of unbalanced reciprocating parts, and on the other hand what proportion they form of the total locomotive oscillations from all causes.[43]

In this, the last major paper on the subject read by a locomotive engineer before a professional engineering

institution in Britain,[44] and one which earned its author the George Stephenson Research Prize awarded by the Institution of Mechanical Engineers, we can perceive a number of reasons for this major vibration problem remaining a matter of concern throughout a whole century. A successful solution to such a complex issue demanded a response which was never forthcoming although developments had made such a task imperative by the late 1930s and contingent upon the return to post-war normal conditions the conduct of appropriate scientific investigations was envisaged. Something of general applicability, quantitative and reliable was an urgent requirement for future use if locomotive design was to be optimised in this respect. Current methods of assessment suffered a number of deficiencies. Physiological sensation and his professional expertise enabled an engineer riding on the footplate to distinguish abnormal from normal vibration but this exercise had its limitations. Thus a two-cylinder engine weighing 55 tons and converted to nil reciprocating balance had sufficient shuttling motion to cause discomfort on the footplate while another two-cylinder engine weighing 86 tons had run for eight years in the same condition of balance without eliciting adverse comment on its riding qualities. This situation, of course, confirmed the theory that the disturbing forces have a smaller effect on heavier machines.

Dynamometer records showing variations in drawbar pull although quantitatively more precise are to an unknown extent vitiated by the inclusion of spurious responses to other factors such as the riding qualities of the locomotive and tender and influences external to the engine itself for example, track

condition.

The possession of a cine-camera was obviously a new instrument in the hands of railway engineers and its successful use by the Research Department of the LMSR was briefly described by W.A. Stanier in his Presidential Address to the Institution of Mechanical Engineers in 1941.[45] Its role in revealing wheel lift, illustrated above, Fig.7.3, is described in greater detail by Cox in his paper. Like balancing, the coning of rolling stock wheels was also a topic which engaged the attention of engineers from the earliest days. By means of a periscope and cine-camera the behaviour of wheels, with profiles ranging from the standard contour of the 1 in 20 taper to a cylindrical tread (favoured by Rankine many years earlier), on the rail head was carefully studied. These tests led to the adoption of a conical profile of 1 in 100 as the most satisfactory design for all main line stock. Indeed the compromise nature of the solution to engineering problems, and a parallel with the balancing problem is demonstrated by this particular piece of experimental work. Rankine's ideas were vindicated. Cylindrical wheels gave the best results, but only at a price; upon contact with the rail the flange tended to maintain this position, until separated by passing through points or rounding a curve, promoting unnecessary flange wear. Overall, the 'best' solution just had to be an acceptable balance between rolling characteristics and economic life.

Photography as a technique available to the industrial research worker acquired an enhanced value with developments both in film and camera technology. After nationalisation

similar studies on the lateral oscillations of the coach wheels of a multiple-unit electric train were carried out on the London Midland Region of British Railways. A detailed report of all this work was the subject of a paper presented to the Seventh International Congress of Applied Mechanics, held in London in September 1948.[46] The availability of an extended range of instrumentation presented locomotive engineers with the means of adopting more scientific methods of measurement essential to an accurate determination of the effects of disturbing forces generated within the locomotive itself. By the time of Cox's paper, although suspended because of the war, work had been started on the locomotive testing station at Rugby, and its ultimate value was perceived. As a participant in the discussion on the two papers presented to the Joint Meeting of the Institutions of Civil and Mechanical Engineers W.A. Stanier commented upon the disadvantaged position of the locomotive engineer who, for many years, had lacked adequate means for measuring the effects of his actions. Better times ahead were envisaged as was the need for properly conducted experimental work,

> ...much investigation was still required to reduce the problem to its elements and establish facts upon which decisions for future practice might be based.[47]

Almost at the end of new locomotive design in Great Britain, then, the potential for higher speeds and the demonstrated possibility of wheel bouncing under certain

circumstances directed the attention of designers to the need for a further reduction in hammer-blow. The conclusions of Cox were clear. For the highest speeds, three- and four-cylinder locomotives were the most desirable with the latter type preferable from the point of view of hammer-blow. Two-cylinder engines required some balance of reciprocating parts, the amount depending upon individual locomotive characteristics, with a minimum of 40 per cent recommended for British engines in the weight range 65 to 70 tons.

Disturbing effects producing longitudinal and nosing oscillations were shown to be dependent upon the weight and length of the engine, the weight of the unbalanced portion of the reciprocating masses and the drawbar spring characteristics. They were shown to be independent of the vehicle speed. The permissible magnitude of these oscillations, which determined the degree of balance required, was governed by a number of factors, including the riding comfort for the engine footplate personnel, and train passengers, safety, maintenance costs and wear and tear.

The theoretical consideration of these oscillations, which formed the latter part of Cox's paper, led the author to his ninth, and final conclusion.

> Practical experience so far recorded tends to support the theoretical conclusions. It is, however, very scanty, and when normal conditions return, scientific investigations will be required, not only to establish the precise effects of the unbalanced parts on the

> locomotive, but also to define the limiting value of the disturbances which can be admitted. More experimental verification is needed as a prelude to any large-scale reduction in hammer blow.[48]

From the 1840s to the 1940s, as this study has shown, the subject of locomotive balancing occupied the attention of engineers. Throughout this whole century the topic was constantly referred to in the deliberations of the professional engineering institutions and a number of papers were specifically devoted to it, but a hundred years after the subject emerged as an important parameter of locomotive design the inconclusive nature of the work undertaken was manifest and the problem remained unresolved.

At the Joint Meeting of the Institutions held on 16 December 1941, at which Cox's paper, discussed above, was delivered, the civil engineer's view of the matter was presented in a paper by Sir H.N. Colam and Major J.D. Watson.[49] Based on their experience in India, where investigations of locomotive balance revealed overbalance on metre-gauge locomotives in the range +51 per cent to -15 per cent and on broad-gauge engines from +80 per cent to -50 per cent, the authors concluded that reciprocating parts needed no balance at all. In this respect their findings were in marked contrast to those of Cox although as they admitted their experience had been gained 'at what some railways may consider comparatively low speeds'. They were at one with him, however, on the need for even more work and on this theme their concluding remarks are equally clear and forceful.

> A good deal has been written and said about locomotive balancing in recent years, and it might be contended that the subject may now be allowed to drop. The Authors, however, are of the opinion that this is a mistaken view, and that the subject is of increasing importance. There has been a widespread move to increase railway-speeds in most countries and there are already indications that this will introduce new troubles. In America it has been discovered that, with certain locomotives at very high speeds, the main driving-wheel actually lifts clear of the rail at one point in its revolution. Apart from any risk of derailment entailed, this must increase rail and bridge stresses to dangerously near to, or even beyond, the safe limit. The Authors' view is, therefore, that a prima facie case for abolishing overbalance has been established, and that if locomotive engineers wish to continue this practice, they must prove that it is necessary. It is certainly expensive.[50]

These expressions of firm resolve and the promise of an ultimate harmonisation of locomotive and track into a designed and compatible system never came to complete fruition. Only insofar as success can be measured by the absence of catastrophic failure can the 'machine-ensemble' regarded as a successful union between the steam locomotive and track by M. Duffy[51] be accepted as a valid model in assessing railway engineering technology. Avoidance of such failures resulted

largely from a state of acknowledged ignorance provided for by conservative design and ample factors of safety. This fortunate and operationally satisfactory situation results almost entirely from the cautious advances made by locomotive engineers in extrapolating from current practice within the paramount criteria of reliability and availability. Innovations that involved risk, and many worthwhile ideas do, were not seriously contemplated. Essentially, progress was achieved with precious little theory and not much more experiment in the sense of consciously designed and conducted investigative tests. British locomotive design evolved, and the evidence suggests that it was evolution rather than development (in the sense of resulting from the endeavours of research and development departments characteristic of many twentieth century industrial concerns). The process was based upon the combined efforts of past experience, trial and error methods and the engineering instinct of those engaged in the work. With the passage of the years, of course, railway engineering did develop its own theory not as an autonomous railway engineering science but as a multi-disciplinary corpus of knowledge covering the many aspects of railway technical activities. Wide as the range was, extending from civil engineering to thermodynamics, the mechanics of the train received little attention.[52] Churchward's locomotive testing station, opened at Swindon in 1904 gave an example that was not followed for many years and despite Gresley's constant lobbying, intensive from the time of his Presidential Address to the Institution of Locomotive Engineers[53] in 1928, for a national stationary testing plant, he

did not live to see the Rugby establishment commissioned.

Of course, the extent to which 'theory' in the sense of abstract scientific, mathematically expressed, ideas could contribute to successful steam locomotive design is an interesting topic for speculation. It is a matter of fact that no locomotive, anywhere in the world and by whatever process designed and developed, occupied a position of splendid isolation because of its incontestable superiority over all others. Certainly some Russian locomotives whose design was based on an array of mathematics and formulae that would have made any British 'steam' draughtsman 'blink' were, according to Cox, 'ordinary to a degree'.[54] Despite the strong 'theoretical' element in Russian locomotive design largely attributable to the involvement of academic engineers in the process, locomotive engineering in that country was not outstandingly successful in the sense that it did not exert any worldwide influence. Russia remained a net importer, rather than exporter, of locomotive ideas. And in France and Germany, too, where the approach was more theoretical than in Britain and where, in certain instances, influence did extend beyond their national frontiers to modify practice elsewhere, there is no evidence to indicate that locomotive performance was more successful than here. On the other hand American practice, unsophisticated but nevertheless continually meeting the demand for more power by big, robust locomotives suited to the relatively poor track of a vast country (compared with British standards), was as sound, straightforward and successful as any. Furthermore, its influence was world-wide and extended to Australia, India and

Russia.

The momentum of the progress achieved during the 1930s carried locomotive engineering to the very brink of what could have been the culminating piece of work which would have established the dynamic factors of design on a rational scientific basis; that is, a thorough examination of the vehicular behaviour of the locomotive comparable to that carried out on bridge structures by the Bridge Stress Committee. As has been seen, the need for the work was recognised and with the completion of the stationary test plant its successful execution was confidently anticipated. But Britain and indeed a large part of the world was engulfed in World War II and the state of normality, envisaged by these engineers, never returned. Other factors, almost entirely of a non-technical nature brought about the demise of the steam locomotive with unsuspected haste.

3. The Post-War Period

Deterioration of locomotive stock due to the combination of arduous service with minimum maintenance during the war years made the resumption of the outstanding performances of the late 1930s impossible to achieve in its immediate aftermath. Even if other pre-war conditions had been instantaneously restored the state of the entire rolling stock of the four railway companies would have prevented a quick return to former speed schedules. But the other conditions necessary for the provision of an excellent, high-performance, railway service had changed irrevocably too. Social, economic and political factors together cast a cloud of uncertainty and indecision over the

railway industry. The General Election of 1945 brought to power a Government committed to the nationalisation of all inland transport and so from the very beginning the railway companies were deprived of the motivation to plan for long term development. This is not the place to examine all the factors involved but the subject is of considerable importance to the historian of technology in illustrating the re-direction of a successful technology, at the very period when it possessed the potential to attain its greatest achievement, by non-technological factors. These changes have been surveyed in some detail by Cox[55] and also by Johnson and Long.[56]

Of relevance to this study however is the situation existing during the late 1940s and described by a contemporary commentator,

> The time and thought of a railway chief mechanical engineer today are devoted mainly to conciliating labour; to avoiding or ameliorating those forms of activity on which organised labour might conceivably impinge; and to keeping engines out of shops and sheds as long as possible despite a much lower standard of maintenance and performance.[57]

Reduction of maintenance costs became the major determinant of locomotive design and operation even if, to some extent, this was gained by some forfeiture of fuel economy and performance. Whereas in former years fuel economy was regarded as the hallmark of cheap and efficient operation the cost of

labour, which doubled over the period of the First World War and thereafter continued to feature as a major and persistently increasing expense in railway working gave stimulation to every possible means of reducing these costs.

Although on nationalisation, which took place on 1 January 1948, the decision was taken to continue with steam traction, by April the suggestion had been made by Sir Cyril Hurcomb, Chairman of the British Transport Commission, to the Railway Executive that a committee of non-engineers should be formed to examine the possibility of alternative forms of motive power. By the end of the same year this body had started work and when, in October 1951, it reported it recommended experiments, on a large scale, to investigate the economics of both electrification and Diesel traction. Thus from the very beginning the future of steam traction was in doubt. As an interim measure to cover requirements until the projected standard British Railways locomotives appeared designs of the former group companies were perpetuated and indeed the total number of such engines built, that is, 1,538, exceeded by a large margin, the 999 standard engines constructed. In retrospect it is dubious whether this exercise was worthwhile from either an economic or an operational consideration. Almost certainly reliance on the established designs to the very end would have proved just as satisfactory.

As it was, the grand finale of locomotive design in Britain demonstrated once more the improbability of designing a steam locomotive that could go into service without the customary batch of adjustments and modifications. Over one

hundred years' experience was no guarantee of immediate success and the 'Britannias', the first of the range to appear, displayed some of the age-old classic failures including broken pistons due to water carry over, bent side rods and cracked frames. Nevertheless, these troubles were quickly diagnosed and corrected and in sum total they were insignificant compared with later problems in implementing Diesel traction.

From the preliminary planning stage it was definite that there was to be no return to earlier standards, and the Report of E.S. Cox, dated 14 June 1948, in the third of his main proposals, stipulated

> That the whole trend should be toward simplification, good accessibility of all parts requiring attention, and reduction in time required for repairs and servicing.[58]

Apart from the proposals for one type of four-cylinder engine, in Power Class 8, but which was eventually built as a three-cylinder locomotive, the whole range marked a reversion to the two outside-cylinders species of machine. The recommendations of the Bridge Stress Committee for the use of three- and four-cylinder locomotives and the excellent performances of such engines during the 1930s were disregarded in the quest for a return to the simplicity of two-cylinders.

The dichotomous nature of British Railways engineering design philosophy with respect to motive power provision is emphasised by the simultaneous insistence upon a return to two-cylinder steam locomotives and extensive trials of Diesel

engines in which twelve- and sixteen-cylinder engines were common and '...a locomotive installation involving six crankshafts, seventy-two pistons and 120 gear wheels...'[59] was not unknown.

In returning to two-cylinder locomotives British practice, at the end, went back to its origins and re-aligned itself with that of North America. Dynamically it was able to make this transition because the design of the various classes conformed to the balancing recommendations of the Bridge Stress committee.

As the following table, Fig.7.7[60] shows, the hammer-blow for the whole engine of several different engine types does not significantly exceed half the limiting value of 12.5 tons specified in the Report.

Class		*70000*	*72000*	*92000*	*73000*	*75000*	*80000*	*36000*	*77000* 82000†*	*78000* 84000†*
Revolving Masses—Weight per Cylinder	lb.	1500	1500	2040	1419	1415	1396	1316	1189	1172
Reciprocating Masses—										
Total Weight per Cylinder	lb.	848	848	865	826	760	757	737	737	564
Percentage Balanced		40	40	40	50	50	40	50	50	50
Unbalanced Weight per Cylinder	lb.	508	508	519	413	380	454	369	368	282
Ratio: Unbalanced Reciprocating Weight per Cylinder to Total Weight of Locomotive	one over	414	390	374	422	400	427	363	350* 451†	391* 526†
Hammer Blow at 5 Revs. per Second										
Per Wheel	tons	2·12	2·12	0·78	2·61	2·40	1·91	2·17	2·17	1·53
Per Axle	tons	2·55	2·55	1·56	3·11	2·86	2·28	2·58	2·58	1·82
Per Rail	tons	5·50	5·50	3·38	6·95	6·49	5·10	5·93	5·93	4·29
Whole Locomotive	tons	8·60	8·60	6·77	8·28	7·73	6·08	7·05	7·05	5·11

**Tender Engine †Tank Engine*

Fig.7.7 Balancing Particulars - British Railways Standard Two Cylinder Locomotives

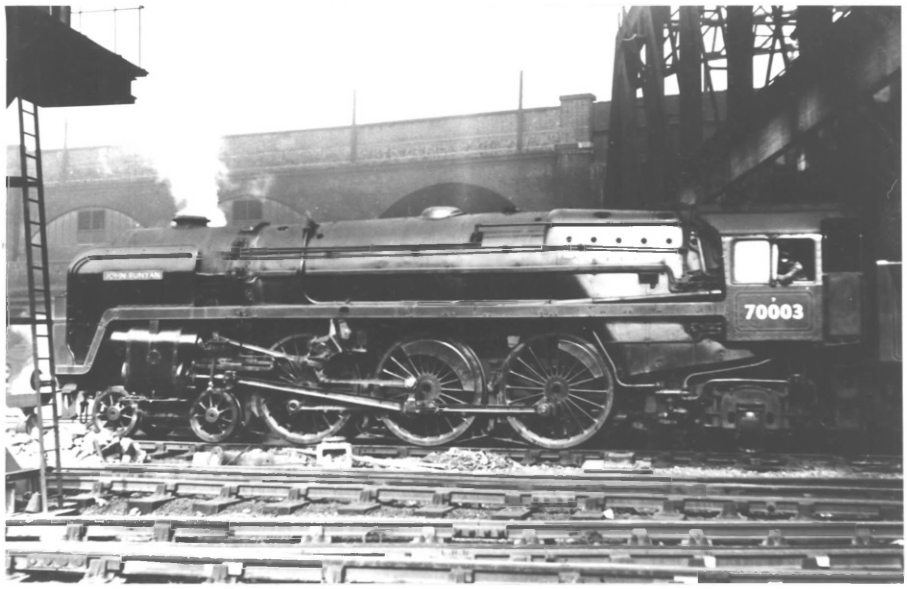


Fig.7.8 British Railways Standard Locomotive 'Britannia' Class 4-6-2, in which 40% of the reciprocating masses were balanced



Fig.7.9 British Railways Standard Locomotive Class 3MT, 2-6-0, in which 50% of the reciprocating masses were balanced

These results were achieved by balancing only 40 per cent of the reciprocating parts on the larger engines, Fig.7.8, and 50 per cent on the smaller machines, Fig.7.9, and distributing the reciprocating overbalance equally between the coupled wheels. Again, the use of alloy steels minimised the mass of motion parts.

Early troubles were encountered due to longitudinal oscillations being amplified through the drawbar resulting in discomfort for the passengers, but these were eliminated by modifying the spring characteristics and without adjustment to the percentage of reciprocating masses balanced.

In Britain, the combination of flat-bottomed, Vignoles, rails giving greater lateral stability and properly balanced locomotives, even those of the notoriously troublesome two-cylinder variety, at last achieved that successful unison so frequently discussed and so long sought.[61] Its practical benefits, however, were of short duration for the days of the reciprocating steam locomotive were already numbered.

Available evidence suggests that this ultimate success was attributable to clear knowledge, provided by experimental work in conjunction with analysis, of the serious consequences of bad balancing practices.

As this chapter has shown, the increase in operating speeds of express trains in the late 1930s stimulated further interest in locomotive balancing and caused another flurry of papers on the subject, those of Brown, Colam and Watson, and Cox, discussed above, and finally the publication of McArd's short monograph as late as 1949.[62]

Other forms of motive power increasingly occupied the minds of Chief Mechanical Engineers. Conscious of the very low thermal efficiency of the conventional steam locomotive they found potentially better alternatives worthy of consideration. Gresley told the Institution of Locomotive Engineers in 1927, 'It is no part of our policy to perpetuate a kind of locomotive that is not economical'[63] although his faith in steam traction was not shaken for in his Presidential Address to the Institution of Mechanical Engineers, October 1936, he spoke of the thermodynamic efficiency of the locomotive as a large field to be explored at the projected locomotive testing station.[64]

By the mid 1940s, O.V.S. Bulleid identified the major disadvantages of the steam locomotive as the use of coal 'as mined', to distinguish it from pulverised coal - still in the experimental stage, the handling of coal and the disposal of ashes, together with its smoke nuisance. Nevertheless, increases in its reliability, availability, economical efficiency, and capacity for further development were seen as factors ensuring its continued and extended use.[65]

Confidence in the future of steam was also expressed in 1947 when H.G. Ivatt, in his only paper to the Institution of Mechanical Engineers told his audience 'It is believed that the conventional reciprocating steam-locomotive is still capable of considerable advance and that the ceiling of operating availability and maintenance cost per mile has not yet been reached' although, again with reference to its thermodynamics he added

> If, for the sake of higher thermal efficiency, or still higher availability, any departure from the simple, inexpensive, rugged steam locomotive of normal aspect is envisaged, the LMSR authorities hold that a complete breakaway from steam towards the internal combustion engine is the logical step to take.[66]

When, in December 1945, Ivatt himself was authorised by Sir William Wood, President of the LMSR, to go ahead with his scheme for two main line diesel express locomotives the transition in British railway motive power, which was to gather momentum rapidly within the next few years was initiated. It is not the purpose of this study to examine the complex array of factors which led to the almost total supersession of steam traction on a world-wide scale in an extremely short time-span. Even allowing for the exceptions to this generalisation, such as the use of diesel locomotives in America from the 1930s onwards and the persistence of 'steam' in some 'mixed' railway systems the demise of the steam locomotive was a relatively hasty affair. Apart from the occasional reference to practice and conditions in other countries where such comment has seemed appropriate this work has concentrated on railway engineering in the United Kingdom, and it is to the situation here that these concluding words apply.

As Cox has indicated, in the USA operating requirements took steam beyond its capacity for economic operation, whilst in Russia political motives were largely responsible, and in other countries shortage of coal or water gave the move to other forms

of motive power impetus and justification. For other countries including Britain he states (and his comment is worthy of serious attention as the opinion of the Mechanical Engineer responsible for locomotive design on the nationalised British Railways)

> But for the rest there was no practical reason, only an emotional one, why steam could not have been replaced in an orderly and economical manner as indeed has been the case in a minority of countries abroad. In its final form it was perfectly capable of continuing to perform its duties with a very acceptable standard of performance and reliability, until it could be replaced, area by area, by more economical successors which had been given time to develop into their natural strides.[67]

He did not doubt or question the inevitability of the transition, based on a rational appraisal of the inherent characteristics of the different forms of motive power. Neither he, nor the former Chief Mechanical Engineers quoted above, saw the dynamical behaviour of the steam locomotive as a limiting operating factor nor as an impediment to further development.

In the light of such authoritative evidence, supported by the findings of this piece of research it seems impossible to sustain M. Duffy's thesis of a successful 'Machine-Ensemble' degenerating over the course of a century to a terminal condition of 'systems disharmony'.[68] Indeed, his model reverses

the process that occurred here. The early experiences of broken track and derailed locomotives gradually gave way to hammer-blow damaged permanent way and shaken structures and ultimately, following the work of the Bridge Stress Committee, to a specified and acceptable standard of loading which permitted high-speed operation of heavy powerful locomotives. At the end of steam traction these locomotives had, in fact, reverted to the 'Stephensonian' model of two-cylinder engines with hammer-blow effects little more than half those permitted. Thus, so far as its dynamic behaviour was concerned, rather than having reached the stage of Duffy's 'design impasse' the steam locomotive was perceived to be capable of rendering good service by the engineer responsible for design on British Railways.

If the envisaged experimental work, the meticulous detailed investigation, had taken place there was a distinct possibility that, with a greater comprehension of the dynamical behaviour of the locomotive, further advances could have been made. Regrettably such work was never carried out because the Modernization Plan for British Railways projected the elimination of steam traction. The reasons for this were

(a) the growing shortage of large coal suitable for locomotives;

(b) the insistent demand for a reduction in air pollution by locomotives and for greater cleanliness in trains and at stations;

(c) the need for better acceleration; and

(d) the wasteful use of labour on unattractive tasks for which it would be increasingly difficult to find staff.[69,70]

Thus after one hundred and fifty years of service to the country a mixture of social, economic and environmental factors brought steam traction to its end. And the problem of balancing, tackled with varying degrees of diligence and success throughout almost the entire period, finished with it. Finally, then, the problem was not solved, it merely ceased to exist.

References and Notes

1. Department of Scientific and Industrial Research, Report of the Bridge Stress Committee, HMSO, London, 1928, p.171.

2. In the tabulated details of locomotives included in the report (pp.173-179), a line was drawn to separate those which exceeded the recommended loading limit, i.e. 'to distinguish those whose combined axle load and hammer-blow at 6 r.p.s. exceeds 30 tons or whose combined wheel load and hammer-blow exceeds 18.33 tons'. (p.169)

3. The Great Western Railway was least affected by the amalgamations. Under the Railways Act of 1921 an exempting clause permitted this company alone neither to be wound up nor to change its name. It merely absorbed several small Welsh Companies (The Cardiff, Taff Vale, Alexandra Docks, Rhymney, Barry, and Cambrian Railway Companies).

4. By 1935 the LMSR was operating with 24 per cent fewer locomotives than in 1923 and by reductions in types of equipment, reorganisation of workshops, etc. and the introduction of new types of locomotives the Company was estimated to be showing an annual saving of about £2 million. Dyos, H.J. and Aldcroft, D.H., British

Transport: An Economic Survey from the Seventeenth Century to the Twentieth, Penguin Books, Harmondsworth, 1974, p.330.

5. Lane, B.C., Private correspondence, letter dated 30 March 1987.

6. Details of R.E.L. Maunsell's 'Lord Nelson' Class locomotives are to be found in:

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   (ii) Townroe, S.C., The Arthurs, Nelsons and Schools of the Southern, Ian Allan, London, 1973.

   (iii) Cocks, C.S., History of Southern Railway Locomotives, Journal of the Institution of Locomotive Engineers, Vol.XXXVIII, 1948, pp.749-822.

7. The Engineer, 19 November 1926, pp.559-560. Article entitled 'Southern Railway - Four-cylinder Express Locomotive'.

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14. Reed, Brian, 'Modern European Locomotive Practice', The Engineer, 25 August, 1933, p.177. Table V of this article gives balancing rules and details for a number of 'modern' Continental railways and locomotives.

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16. Poultney, E.C., op.cit., p.129.

17. Campbell, H.A.F., op.cit., p.319.

18. Ahrons, E.L., The British Steam Locomotive, 1825-1925, The Locomotive Publishing Co. Ltd., London, 1927.

19. Cox, E.S., Locomotive Panorama, Vol.1, 1965. Vol.2, 1966, Ian Allan, London.

20. Nock, O.S., The British Steam Railway Locomotive 1925-1965, Ian Allan, London, 1966.

21. Reed, Brian, 150 Years of British Steam Locomotives, David & Charles, Newton Abbot, 1975.

22. Cox, E.S., op.cit., Vol.1, p.99.

23. Dyos, H.J. and Aldcroft, D.H., op.cit., pp.330-331.

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26. Foxlee, R.W. and Greet, E.H., 'Hammer-blow Impact on the Main Girders of Railway Bridges', Proceedings of the Institution of Civil Engineers, Vol.237, 1933-34, Pt 1, pp.239-313.

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37. Brown, D.C., 'Counterbalancing and its Effects on the Locomotives and on the Bridges', Journal of the Institution of Locomotive Engineers, Vol.28, 1938, pp.52-111.

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39. Cox, E.S., op.cit. This photograph is reproduced from Cox's paper where it is Fig.4.

40. Ibid. This photograph is reproduced from Cox's paper where it is Fig.5.

41. Ibid. This photograph is reproduced from Cox's paper where it is Fig.6.

42. Ibid. This diagram is reproduced from Cox's paper where it is Fig.7, p.154.

43. Ibid., p.154.

44. The paper by E.S. Cox was read at a Joint Meeting with the Institution of Civil Engineers at which another paper, by Sir Harold N. Colam and Major John D. Watson dealt with the matter from the point of view of civil engineers. The common concern of the subject is implicit in the publication of both papers in the Proceedings of both Institutions. Additionally, Cox's paper was included in the Journal of the Institution of Locomotive Engineers.

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47. Journal of the Institution of Civil Engineers, Vol.17, 1941-42, Discussion on 'Hammer-Blow in Locomotives' and on the Balancing of Locomotive Reciprocating Parts. Comment by Mr V.A.M. Robertson, p.377. Similar views were also expressed by Lieut.-Col. Sir Alan Mount, i.e. 'When normal times returned the whole subject of the riding of engines on the track would require more investigation, and when the testing-station had got going, with flange stress recording instruments, a great deal of experimental work would be waiting to be done, not only to establish the effects of the unbalanced parts in a locomotive under high-speed operation but also to define the limiting value of permissible disturbances.', pp.373-374.

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61. This harmonisation of locomotive and track appears to have been achieved on all the major railway systems throughout the world. For example, the stringent restrictions, limiting hammer-blow, implemented in the European countries has been mentioned at the beginning of this chapter. Likewise, the difficulties encountered in the United States due to high-speed running, during the 1930s, were overcome by the adoption of cross-balancing, also referred to earlier in this chapter.

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Chapter 8

CONCLUDING REMARKS

A historiographical survey of the British steam railway locomotive clearly reveals a vast lacuna in respect to the technical aspects of their design. This deficiency, however, characterises the whole history of engineering design, a topic which remains elusive and which has received little scholarly attention.[1] Neither the histories nor the, apparently few, contemporary records that have survived explicitly reveal design procedures and engineers, employed to build and operate locomotives (and, generally, any other artifact) were not in the habit of recording accurately their working methods and the reasons for their decisions. Even the odd document that remains is frequently of limited value to the historian since it merely indicates what the engineer did, or perhaps proposed, while the fundamentally important and more interesting motive for his option remains undisclosed. Indeed, in many cases, it is likely that he would deliberately avoid revelation to protect his own advantage. The truth of this is hardly modified by exceptions such as George Hughes' paper read to the Institution of Mechanical Engineers and briefly considered in Chapter 5. To a certain extent, of course, this predicament confronts all historians because the existence of complete evidence would diminish the need for research although the tasks of synthesis and presentation would remain.

For these reasons, then, the history of railway engineering problems is difficult to penetrate because of the lack of proper resources and this very limitation has provided

one of the major challenges to this thesis. That is, to investigate in what depth and detail it is possible to examine a specialised, significant aspect of locomotive design which is, after all, one of the most prominent of all English engineering enterprises.

Despite these limitations there is ample authentic contemporary evidence to indicate that the balancing of the steam locomotive was an acknowledged responsibility of the engineer from the mid-1840s onwards. Regrettably, virtually nothing is known of the lives and professional work of G. Heaton, W. Fernihough and H. Nollau but, undoubtedly, their contribution to the establishment of the subject of 'balancing' as an integral part of locomotive design and operation was crucial.

The Proceedings of the Institutions of both the Civil and the Mechanical Engineers, Government Reports and the pages of Engineering and The Engineer, the main documentary sources used for this study, provide innumerable references to the subject. From the middle of the nineteenth century there is a rich, varied and widespread selection of published material -and this monograph has not attempted to summarise it all -providing abundant evidence that the topic remained within the consciousness of engineers. This fact, of itself, however, is not particularly significant because as the foregoing chapters have shown the focus of the problem changed over the years and it was not until the 1920s, following the investigations of the Bridge Stress Committee, that the subject was treated with anything like the seriousness it merited.

Balancing the two-cylinder locomotive posed a problem not amenable to a definitive solution because the exercise was a compromise and as conditions changed so did the necessary degree of compromise. Difficulties arose when practice crystallised in the form of universal design rules which failed to satisfy new circumstances. The proportions of reciprocating balance advocated by Le Chatelier and Clark were unquestioningly accepted as 'standard' and applied long after their validity was outmoded. Preoccupation with the thermodynamical aspects of the locomotive led to a relative neglect of its dynamics, a situation which persisted almost throughout the entire life of the two-cylinder engine in Great Britain. It certainly appears to have clouded the perception of the problem of vehicle stability which can be seen as culminating in four distinct phases, each of them, in turn, highlighting the balancing problem.

During the earliest of these periods, from the 1840s, when the engineers were grappling with the difficulties of achieving safety at speed their major concern was the diminution of the 'sinuous' motion and this was secured at the expense of introducing vertical forces acting on the rails. It has been shown that the potential hazards associated with this expedient were consciously discounted by responsible engineers such as Fernihough, Clark, et al.

From the 1870s to the 1890s, the appearance of heavier and more comfortable trains running to faster schedules inevitably led to the construction of bigger and more powerful locomotives. Unquestionably, these heavier engines running at

higher speeds led to an increasing awareness among locomotive engineers of the effect on the track of these vertical forces. During this phase the graphic, if rather inexact, expression 'hammer-blow' to describe the phenomenon entered the vocabulary of the railway industry.

The early years of the twentieth century witnessed the mounting anxiety of the civil engineers brought about by considerations of bridge and track maintenance and replacement. This trend reached a climax with the work and the subsequent Report of the Bridge Stress Committee during the 1920s. The pivotal role of this Committee in laying bare the inadequacies of locomotive balancing practice from a 'systems' viewpoint cannot be overemphasised. But its recommendations were not a lasting panacea. So far as the locomotive was concerned it indicated the need for further methodical investigations. Nevertheless, resulting from its work an immediate improvement in balancing procedures together with refinements in other aspects of design, mentioned in Chapter 7, did permit express passenger locomotives to achieve unprecedented levels of performance. However, the increased speeds, exceeding those envisaged by the Bridge Stress Committee brought to the fore the reality of wheel lift under operating conditions.

By the 1940s, the ill-defined effects of horizontal forces on the locomotive were again a matter of increasing concern to engineers and the need for further work on this topic was clearly expressed. Thus the focus of attention was once more directed to that aspect of the matter which occupied the engineers a century earlier. Abandonment of steam traction

prevented this work from being undertaken but its very projection took the subject back to its starting point. After a hundred years, then, the task of balancing the locomotive was not complete and further work remained to be done. In this respect, however, the balancing problem was not unique and other issues, especially tribological problems associated with bearings and lubrication, the coning of wheel treads, valve events and steam circuits occupied the minds of engineers throughout the life of the Stephensonian locomotive.

The evidence leads to the conclusion that the engineers overcame the troublesome aspects of locomotive dynamics in a piecemeal fashion as they manifested themselves and in no way sought technical perfection. An exception to this, of course, is those who specifically designed engines with good balance characteristics as a prime objective. Nor is this surprising; their endeavours were directed towards the economic success of their company. The railway companies which employed them were commercial enterprises in which all the departments were expected to contribute to the overall profitability of the company. It is essential when viewing the balancing problem and the response of engineers to it, to constantly bear in mind the inseparability of the economic and engineering factors of railway transport. Top priority in the eyes of managers and shareholders was commercial success which, in the final analysis, depended upon the cost of a net ton-mile and this in turn accentuated the necessity of minimising total operating costs. Important though efficient bridges, track and locomotives were in contributing towards success, there were

also many other factors both economic and technical which also had to be considered. Concepts of efficiency were rudimentary and took many years to develop.

So far as the locomotive was concerned a major criterion of its success was reliability, a characteristic measured in terms of availability. This was determined by the number of engines available for normal service each day, commonly expressed as a percentage of the total locomotive stock. Although employed by railway companies as a measure of performance this yardstick hid as much as it revealed. It concealed some service problems which, although not responsible for traffic delays, were potentially expensive to control. Of these, permanent way maintenance was significant, but this did not appear with forceful clarity until the years following the Report of the Bridge Stress Committee when awareness of the interaction between train and track led to a conscious 'systems approach' to the dynamics of the situation.

Unquestionably, the efficient, harmonious working together of locomotive and track involved a genuine dynamical problem. Eventually, the lesson was learned that ignorance, or neglect, of the laws of physics cost money. By excluding the notion of efficiency, which became more difficult in the years after the First World War as escalating operating costs plus growing competition from road transport services forced themselves to the attention of management, it is also possible to regard locomotive balancing as a 'non-problem'. Unbalanced and badly balanced locomotives could be, and were, used without catastrophic results. On branch lines, on short journeys, on

long overnight hauls there was no demand for very high speeds and even on the prestigious express services the somewhat haphazard use of rim weights proved adequate because as higher speeds became customary the size and the mass of locomotives grew with an increase in the longitudinal inertia of the vehicle which masked the real situation. The steady-running G.W.R. 'Stars', giving the appearance of well-balanced engines, were in fact delivering a hefty hammer-blow to the rails. On the other hand, as illustrated by the 'Sevenoaks' disaster, a locomotive which behaved well on good track could give an unsatisfactory performance on poor track.[2]

As Chapter 4 has shown, engineers were never short of ideas to produce a better balanced locomotive and in Britain innovative designs appeared well into the twentieth century. Schemes involving belt, chain, or gear driven balance masses and the use of contra-rotating masses were not prominent for the good reason that getting the large masses required in the plane of the pistons involved a degree of complexity that deterred all but the unrealistically enthusiastic in an environment where the willingness, or the opportunity, to develop and exploit them was lacking. Such arrangements had no established precursors. The steam engine, itself, the motor car and the aeroplane provide classic historical examples of the difficulty of designing successfully without a precedent.

Virtually all of the projects capable of practical development and adoption were three- and four-cylinder engines although when, in due course, these multi-cylinder types were put into operation it was to provide more power rather than for

dynamic improvement. Of course, it was possible to accomplish both objectives with appropriate design. The fact that they were not secured when the chance presented itself suggests that the actual achievement was determined more by the level of ignorance than by the application of scientific knowledge.

Within the railway industry the two-cylinder locomotive provided a precedent which remained dominant from beginning to end. The reasons for this are largely attributable to non-technical factors. Design, therefore, must be appraised through the eyes of company managers, shareholders, operating personnel, maintenance mechanics, civil engineers, and so on, all of whom were likely to hold different notions as to what constituted a 'successful' locomotive. Few of them were likely to be interested in the sophistication of a 'scientifically' designed engine, that is, one possessing optimum dynamic characteristics. In design, material availability and quality, a skilled work-force, production facilities, costs of labour, manufacture and maintenance were all significant considerations. Thus the social, economic and industrial environments interacted in determining the major parameters of locomotive design (this, of course, was generally true of other areas of the evolving railway system). The milieu produced a convergence of factors which dictated perpetuation of a basic design commonly regarded as economically acceptable and known to be practicable in terms of the available technology. Theoretical perfection, even if esteemed as an ideal was not accorded top priority by the railway world during the nineteenth century. Nor is it the primary criterion in the overwhelming number of man's

technological enterprises in any age. As noted above, the main requirement was reliable machines, with a long operational life, capable of contributing to the profitability of the company and if this philosophy encouraged extreme caution in adopting design innovation it appeared to those with responsibility a prudent discharge of their duties.

During the years of rapid expansion of the railway network characterised by feverish activity to meet insatiable demands for tractive power attention was focused on construction rather than efficient behaviour. Afterwards, when conditions became more settled, locomotive performance and especially economy of operation occupied the attention of management to a far greater extent. However, this shift of emphasis appears to have concentrated on fuel costs to an unwarranted degree rather than an overall evaluation of the economics of operation of the 'train-track' combination.

Improvement in the situation could have been attained had it occurred to railway management to compare the cost of 'complex' but better-balanced locomotives with the cost of track maintenance and renewal due to the use of badly balanced engines. Such assessment would almost certainly have inculcated a more open-minded attitude to some designs of 'balanced' locomotive. Prevailing conditions of management, organisation and structure, until well into the twentieth century, do not permit the historian to regard this as a real possibility. Quite simply there was not a meaningful quantified, awareness of the dynamic consequences of incompatability between machine and permanent way. As this thesis has repeatedly emphasised, the

separation of mechanical and civil engineering departments, paralleled by similar isolation of accounting and budgeting activities effectively masked vitally important technical and financial factors for many years. Only in the aftermath of the findings of the Bridge Stress Committee could such concepts as 'preventative maintenance' as opposed to repair of damage emerge and find acceptance as a rational approach to the 'wheel-rail' interaction and, indeed, to other parts of the railway system.

Unambiguously this confluence of social, economic and technological factors reveals the human aspect of engineering projects in which the forces guiding technical advance are often non-technological in origin. The history of technology provides a salutary lesson in driving this message home and in emphasising the difficulties and dangers in attempting to interpret history in conformity with a predetermined paradigm.

Germane to this study is M. Duffy's interesting attempt to integrate historical studies, with the methods of engineering design and systems analysis in establishing 'technomorphology' - the term that Duffy uses for the investigation of technological change - with the declared utilitarian objective of assisting the planning of engineering, business and industrial activity. A major contention of his Newcomen Society paper 'Technomorphology and the Stephenson Traction System' is that 'systems-disharmony' which resulted in abandonment of the steam locomotive was brought about principally by dynamic incompatability between engine and track.[3] However, his conclusion does not withstand the weight of the evidence examined here. The reasons for this apparent conflict of

results obviously merit some comment. Clearly the areas of interest are not congruent and Duffy's work in the field is mainly concerned with 'track-working' and American practice and this is reflected in the source materials used. In contrast to this study, his work gives little consideration to the Proceedings of the Institution of Mechanical Engineers, especially the early papers, and pays scant detailed attention to the Report of the Bridge Stress Committee.

Concentration on the American scene naturally leads to conclusions different from those emanating from the study of British railway engineering because the situation was vastly different there. With a larger loading gauge, permitting everything to be scaled up, heavier axle loads were allowed and exploited. Furthermore, haulage distances were much greater and traffic density and consequently track occupation were lower leading to quite dissimilar operating conditions. Whereas in Britain railway companies usually built their own locomotives, in America they were built by locomotive companies although the design generally involved the participation of the purchaser. Furthermore by the 1930s British passenger express locomotives were capable of handling the maximum size trains that could be accommodated by station, platform, sidings, and other service facilities and this tended to retard the demand for even bigger and more powerful engines while in the United States of America it continued unabated. Additionally, the essentially different philosophies on the two sides of the Atlantic were significant. American locomotives were designed for a much lower level of maintenance and a shorter life than their British counterparts,

which in turn promoted more rapid progress there. But despite this, and notwithstanding the gigantic proportions of some locomotives, balancing practice in America was fundamentally poor, inferior to that in Britain and Europe, and not until the 1930s did 'cross-balancing' become the norm.

Interpretation of the same evidence, even when it is free of internal conflicts - such as in the Beyer Peacock documents discussed in Chapter 3 - also allows different conclusions to be drawn. This is amply borne out by Duffy's comments on the 'Planet', the first locomotive with two horizontal inside cylinders. In several places he asserts that this configuration was chosen to bring the centre lines of the cylinders as close together as possible to reduce the nosing couple.[4] Unquestionably this was an advantage of the layout but almost certainly an unperceived one in 1830 when the dynamics of the locomotive were just not understood. If the anachronistic use of the adjective is allowed, it is permissible to claim that thermodynamic factors were more readily appreciated. The testimony of Robert Stephenson himself reveals that the arrangement was dictated by the desire to locate the cylinders within the smokebox to prevent the condensation of steam in the cylinders and the consequent power loss.[5]

Other illustrations of the importance of interpretation were brought to the fore in the discussion following the Newcomen Society paper referred to above.

It is not the place, nor the purpose, here to make a detailed examination of Duffy's writings on the subject but merely to reiterate that his conclusion that dynamic factors

> ...in particular those associated with the periodic loads...imposed on the track...[6]

brought about the obsolescence of the steam locomotive is not corroborated by this study. Indeed, as Chapter 7 has shown, the British Railways Standard Classes achieved a degree of harmony between locomotive and track never previously found in British railway practice; and this was accomplished with two-cylinder engines. In reality the demise of the steam locomotive in England was brought about by a complex combination of factors which included an escalation in coal prices and the reduced availability of coal of the right size for locomotive working, together with increased maintenance costs and the unsocial working conditions associated with steam traction.

Although it is generally acknowledged that following publication of the Report of the Bridge Stress Committee the subject of locomotive balancing was established on a more 'scientific' basis in Great Britain the precise nature of the contribution of 'engineering science' to the development of the locomotive is not easily assessed. Certainly the competition, from other modes of transport, noted above, provided railway companies with an incentive to promote, by every means, economy and efficiency. Contributory factors to securing these were the use of higher pressures, temperatures and speeds and so there was an increasing role for 'science' and design engineers knowledgeable of scientific principles. However, the availability of 'scientific knowledge', technical papers, etc. is not of itself a guarantee that design will proceed on a

rational basis. This is not to suggest, of course, that the early work regarded as scientific was necessarily analytical; indeed the opposite is usually the case. Papers presented to the engineering institutions were essentially descriptive and only gradually did mathematical analysis become more prominent in their Proceedings. Even then it is not obvious that it was extensively used by designers.

Problems amenable to mathematical treatment, although perhaps raised by practical requirements, nevertheless frequently present no more than a fascinating intellectual challenge to the theoreticians who will tackle them with enthusiasm but with little regard for the actual application. It is by no means certain that Redtenbacher's differential equations arising from his studies of the disturbing effects on the locomotive were ever of practical importance.[7] Likewise, for example, it is doubtful whether Lagrangian mechanics[8] or Bennett's paper[9] to the Fifth International Congress of Mathematicians contributed much to day-to-day design. Such works demanded a level of mathematical understanding and ability not found in British engineers. For many years the objective of those with ultimate responsibility for design appears to have been to reduce the task of their largely anonymous subordinates, the draughtsmen, technical assistants and ancillary staff who actually carried out the detailed design, to a routine procedure performed without understanding. This situation was clearly widespread in the engineering industry. For example, Mr J. MacFarlane Gray, a Member of Council of the Institution of Naval Architects, told his audience in 1900,

> I have...further improved my method, which now enables the draughtsman to get all the information...without any calculation and without mathematics. In my own experience I have never known trigonometry...to be used in any drawing office....any problem in balancing a four-cylinder engine is solved without mathematics.[10]

At the same time Professor Dalby's method reduced the exercise to accurate drawing, while as late as 1939 A.I. Lipetz, Chief Consulting Engineer, responsible for research at the American Locomotive Company paid tribute to a paper which '...used simple arithmetic instead of elaborate mathematics.'[11]

This deficiency also put limitations on the civil engineers. In his thesis, The Role of Structural Models in the Design of British Bridges 1800-1870, Dr Denis Smith has shown how they, faced with the demand for bridges to carry the unprecedented loads introduced by the railway train and bereft of facility with mathematical structural mechanics used structural models as a design aid.[12]

Mathematical complexity did not necessarily possess intrinsic merits over less sophisticated methods and, in what was an integral part of locomotive design, there was clearly a requirement to replace full analysis by a more conveniently used design procedure. Nevertheless, the low level of intellectual capacity catered for by such provision and sentiments was not conducive to competent, rational design.

The lack of mathematical ability in design staff was almost certainly paralleled by a similar deficiency in

scientific knowledge and this retarded progress. If there was a point where the design of locomotives was crucially related to science it was undoubtedly on the matter of the steadiness of locomotives at speed. To cope with this problem meaningfully demanded a knowledge of dynamics and yet, as the evidence has shown, many locomotive designers (and civil engineers, too) only partially understood what they were doing. Generally, all concerned responded inadequately; simply, they were unaware of the true state of affairs which, in turn, helps to explain the persistence of the problem. Largely, this situation can be attributed to historical reasons.

Locomotive design was primarily dictated by operating conditions and was developed principally to meet changes in these conditions although the origins of any particular design could well be a nebulous mixture of factors and influences, including experience with other locomotives, the work of other engineers, prevailing economic circumstances, the manufacturing equipment and facilities of the builder, or the strength of civil engineering works. Design advanced, then, not by impressive steps but rather by persistent small increases in dimensions, power ratings and other parameters and always to improve reliability. This procedure of what might be termed adaptive design required only minimal intellectual effort. Because the various problems associated with the design and construction of the locomotive had already been settled, science probably appeared to have little worthwhile to contribute to the exercise.

Current ideas of the engineer, technically

well-educated, with a good knowledge of mathematics, physics and engineering took a long while to develop. Essentially those British steam locomotive men who rose to become 'Locomotive Superintendent' or, as they were later designated, 'Chief Mechanical Engineer' were practical mechanics trained as apprentices or pupils. Their theoretical knowledge was usually acquired at evening classes. However weak this may have been it was frequently compensated for by the long period of training which endowed many of them with an excellent grasp of sound engineering practice. By intuition and adaptive design techniques they were able to create engines equally good if not superior to those designed on a more theoretical basis by European engineers.

Nevertheless, it cannot be disputed that gradually the role of theory was acknowledged and design methods became more scientific. But, as this study has shown, notwithstanding the contribution of 'engineering science', balancing practice in Britain, Europe and the United States of America far from being identical, or nearly so, was markedly different. In all three regions the engineers developed an acceptable compromise. Thus the problem of balancing the steam locomotive provides an excellent illustration of the primary objective of engineering design - to achieve a machine (or other artifact) that will <u>work effectively</u>, that is, safely, reliably and economically. Overall satisfactory performance, then, may be regarded as an attainable 'state of perfection' in contrast to the more elusive and limited 'technical perfection' desired in one particular aspect of design.

Ultimately we may conclude that the two-cylinder steam locomotive, despite its inherent dynamic faults, persisted for so long because as a long-established well-known classic form it proved capable of yielding the extra performance demanded of it as the years passed by. Engineers rose to the challenge and in Britain, even at the end, technically, it was capable of giving more.

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2. In August 1927, the 'River Cray' hauling a train from Cannon Street to Folkestone was derailed near Sevenoaks killing 13 people and seriously injuring 21 others. Criticism of the permanent way led to the re-ballasting of all main lines on the Southern Railway. See O.S. Nock, Historic Railway Disasters, Ian Allan Ltd., London, 1983, 3rd Edn. pp.124-137.

3. Duffy, M.C., 'Technomorphology and the Stephenson Traction System', Transactions of the Newcomen Society, Vol.54, 1982-83, pp.55-78.

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(ii) 'Rail Stresses, Impact Loading and Steam Locomotive Design', History of Technology, Ninth Annual Volume,

Mansell Publishing Limited, London, 1984, p.48.

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6. Nock, op.cit., p.60.

7. Redtenbacher, F., Die Gesetze des Locomotive-Baues. This theoretical treatment was published in 1855.

8. Thornton, D.L., Mechanics Applied to Vibrations and Balancing, Chapman and Hall, London, 1939, pp.45-65.

9. Bennett, G.T., 'The Balancing of the Four-Crank Engine', Proceedings of the Fifth International Congress of Mathematicians, (Cambridge, 22-28 August 1912), Cambridge University Press, 1913, Vol.2, pp.218-234.

10. Schlick, Otto, 'On Balancing of Steam Engines', Transactions of the Institution of Naval Architects, April 1900. The quoted words of Mr J. MacFarlane Gray are from his contribution to the discussion on Schlick's paper. pp.158-159.

11. Lipetz, A.I., 'To the Question of Balancing Reciprocating Weights in Steam Locomotives' reprinted from Transactions of the American Society of Mechanical Engineers, August 1939, p.522.

12. Smith, Denis Patrick, 'The Role of Structural Models in the Design of British Bridges 1800-1870', Doctoral thesis, Department of History of Science and Technology, Imperial College of Science and Technology, London, November 1976.

Appendix 1

GEORGE HEATON

George Heaton, the third of the five sons of Ralph Heaton, was probably born about 1790. His father was a jobbing smith with his own business in Birmingham and in 1794 was granted a patent, No.2010, for a machine for making metal shanks for buttons.

George joined the family business with three of his brothers, John, William and Reuben whilst Ralph, his other brother went into business on his own and his enterprise eventually became the Birmingham Mint. About 1826 the family business which had hitherto been in the father's name became Heaton Brothers. By 1850 it was in George's name, then he took his son and son-in-law, William Dugard, into partnership and the firm traded as Heaton Son and Dugard, and from c.1856 as Heaton & Dugard and such it remained until 1959 when it was absorbed into Delta Metal.

Apart from a letter or two to the Mechanics Magazine, his paper read to the British Association at its Birmingham Meeting, in 1849, and a paper entitled 'On the Importance of Making a Compensation for the Pull of the Air Pump Bucket in the Condensing Steam Engine' read to the Institution of Mechanical Engineers in April 1850 he does not seem to have taken the least interest in publicising his work. This task appears to have been undertaken with some enthusiasm by Dr J.B. Melson. The Birmingham Museum of Science and Industry holds various accounts of Heaton's balancing work but all are secondary

sources and appear to have their origin in reports of Melson's lecture to the Birmingham Philosophical Institution. Here it is important to recognise that his description of the balancing of the pulley on the Earl of Craven's lathe was given some thirty years after the event. The detail in his account suggests that is was based on proper records but of this we have no knowledge. There are no papers in the Craven collection, at the Berkshire Record Office, pertaining to George Heaton's engineering works for the First Earl of Craven.

Melson's lecture included some demonstrations, with simple models made by Heaton to show that inattention to balancing involved a loss of power. For example, in one case he took a model locomotive crankshaft and showed how difficult it was to make it revolve more than once or twice with the greatest force he could exert upon it with his fingers whilst a similar model, having a counterpoise to each crank made several revolutions with the application of the same force.

Then, with a capstan he inserted a brass rod into its head so that it projected equally on each side and then set it into motion by means of a six-pound weight when it turned for 46 seconds and made in that time 241 revolutions. With the rod all out on one side, and other conditions being identical, the capstan turned for only 30 seconds and performed only 50 revolutions.

From such results it is clear that Heaton was making and using models to investigate the subject in a methodical way and to derive from his experiments some quantitative data enabling comparisons to be made and conclusions drawn. This type of work

he appears to have pursued over a period of several years and to have directed some of it to specific railway problems. Indeed, a series of experiments to illustrate the causes of railway accidents were reported in The Iron Times during September 1845. On Thursday the 11th September some of these demonstrations were conducted in the presence of Major-General C. Pasley, Mr J. McConnell and Dr J.B. Melson. On the following Saturday, this journal reported

> Seventeen experiments were made, and the result of everyone went to the effect, that when different pressures are applied to wheels fixed to the same axles, tremulous and jumping motion is the result.

It also commented

> Mr. Heaton, we hope, will be induced to continue his experiments, with a view to ascertain the difference in the motion when the wheels of carriages are independent of each other, and when mechanically united.
>
> To this gentleman great praise is due for the devotion he has paid to the true interests of science....

Despite the reputation earned by his own engineering activities and the publicity given to his work on balancing by Dr J. Melson (it is not unreasonable to surmise that George Heaton occupied a fairly prominent position in the engineering

circles of Birmingham), his death[2] was not recorded in either the technical or the local press. This occurred in the third quarter of 1854 and thus within a few years of his presentation of papers to both the British Association and the Institution of Mechanical Engineers. The fact that he owned and ran an engineering business, was obviously interested in the theoretical aspect of engineering, presented a paper to the newly-formed Institution, and was not unacquainted with James McConnell, the first Vice-President of the Institution of Mechanical Engineers, could lead to the expectation that he would have been a member of a professional body. The librarians[3] of both the Institution of Civil Engineers and the Institution of Mechanical Engineers have conducted an extensive search of their records and confirmed that he was never a member of either body.

His only recognition within the formal annals of the engineering profession seems to be due to his mistaken and confusing inclusion in an obituary for his nephew[4], of the same name, which appeared in the Proceedings of the Institution of Mechanical Engineers in 1904. The writer of this memoir stated that George Heaton was born in Birmingham on 10 January 1833 and then, a few sentences further on, that he contributed a Paper to the Institution in 1850. Obviously he did not refer to the paper itself because its author began by stating that in 1844 he was '...employed to inspect and ascertain the cause of the irregular motion....' Hence the official records of the Institution, based on these two documents, show George Heaton senior to have acted as a consulting engineer at 11 years of age

and as presenting his paper to the Institution at a more mature 17 years.

References and Notes

1. Heaton, George, 'On the Importance of Making a Compensation for the Pull of the Air Pump Bucket in the Condensing Steam Engine', Proceedings of the Institution of Mechanical Engineers, April 1850, pp.26-29.

2. I acknowledge the assistance of Mr J.H. Andrew, of Birmingham, who provided me with information on the year of George Heaton's death, the relationship between the two Georges and other details on the Heaton family.

3. I am indebted to the librarians of the Institution of Civil Engineers and the Institution of Mechanical Engineers who carried out this investigation for me.

4. Heaton, George (Jnr), 'Memoir', Proceedings of the Institution of Mechanical Engineers, December 1904, p.1360.

Appendix 2

DALBY'S SEMI-GRAPHICAL METHOD OF BALANCING

The starting point of Dalby's reasoning is that the effect of a force, with reference to a point is equal to that of an equal and parallel force plus a couple. And this fact he illustrated as follows:

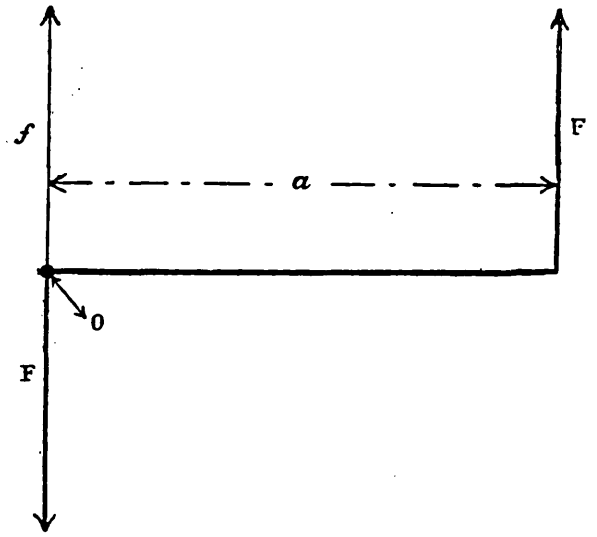


Fig.A2.1 Effect of a force with reference to a point

With reference to Fig.A2.1,[1] then, the force F acting vertically upwards at the perpendicular distance 'a' from the point '0' is equal to, the equal (in magnitude) and parallel force 'f' and the couple of magnitude 'Fa'.

The application of this principle is immediately extended to a three-dimensional situation in which a rigid shaft to which is attached a uniform disc carrying, eccentrically, a

mass M. Rotation of the shaft generates a centrifugal force of magnitude Mw^2r which acts upon the shaft, OX.

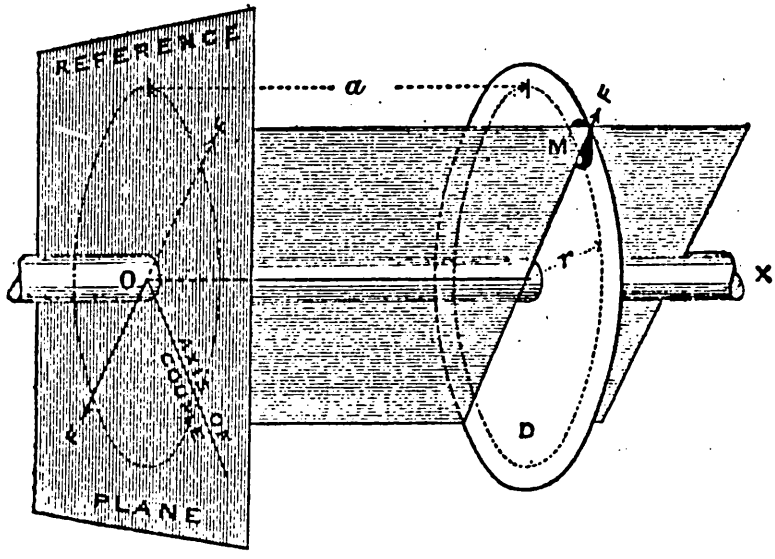


Fig.A2.2 Application of the principle to a three-dimensional situation

and, from the previous elementary consideration, produces the following effects at the point O, which for convenience may be chosen anywhere:

(1) an equal and parallel force, $F = Mw^2r$, acting at O and

(2) the couple Mw^2ra acting on the shaft tending to turn it about O, in the plane (shown shaded) containing the axis of revolution OX, and the radius of the mass M.

It will be observed that this diagram, Fig.A2.2[2], contains what is termed a 'Reference Plane'. The basis of the method is the introduction of the concept of an imaginary reference plane, defined by Dalby as

> A plane at right angles to the axis of revolution containing the point O is the plane in which the transferred force acts...'[3]

and thought of as a sheet or drawing-board keyed to the engine crankshaft, and hence revolving with it, on which the vector summation required by the problem is carried out. On the reference plane, then, the force and couple polygons were to be drawn from elements found arithmetically with the aid of a schedule. In the conventional two-cylinder locomotive there are only two unknown quantities, the forces due to the two balance weights, moments only had to be taken about a point in the line of action of one of the known forces and the other could be immediately determined. Since the forces all act in parallel planes the vectors representing the moments may be drawn parallel to the lines of action of the forces since the only effect of doing this is to turn the whole moment polygon through 90°. Having dealt with the graphical representation of the centrifugal force and couple on the reference plane the author then covered the situation where there were several revolving masses attached to the shaft, indicating that each force was separately referred to the reference plane, leading to a system of forces acting at O together with a system of couples, the total unbalanced effect of the masses being given by, the resultant of the transferred forces acting at O; and the resultant of the couples. For the system to be balanced it was necessary that there should not be a resultant force nor a resultant couple, that is both force and couple polygons should

close. He also indicated that the graphical treatment could be simplified by reducing all the masses to crank radius and, instead of drawing force and couple vectors, and hence polygons, producing 'Mr' and Mar' polygons - a reasonable and justifiable simplification since the factor w^2 (where w is the angular velocity) being common to every mass in the system, from the aspect of drawing merely acted as a scale multiplier.

Dalby illustrated his method by applying it to two engines of the Lancashire and Yorkshire Railway using information supplied by Mr John A.F. Aspinall. A brief summary in Dalby's own words of the procedure follows to show the application of the method to an actual locomotive balancing problem. The data[4] on the locomotive, Fig.A2.3, the diagrams[5] and the schedule[6] are reproduced from Professor Dalby's paper:

EXAMPLE 1.

ART. 8.—*Inside Cylinder Single Engine, 26 inches Stroke—*

DATA.

Distance centre to centre of cylinders.	1 foot 11 inches.
Distance between the planes containing the mass centres of the balance weights	4 feet 11 inches.
Mass of unbalanced revolving parts per crank-pin reduced to 13 inches radius	644 pounds.
Mass of reciprocating parts per cylinder at crank-pin radius	551 pounds.
Proportion of reciprocating parts to be balanced	two-thirds.

The mass to be balanced at each crank-pin is therefore 644 + $\frac{2}{3}$ of 551 lbs. = 1,011 pounds.

Fig.A2.3 Data on Inside Cylinder Single Engine

Fig.A2.4 Elevation

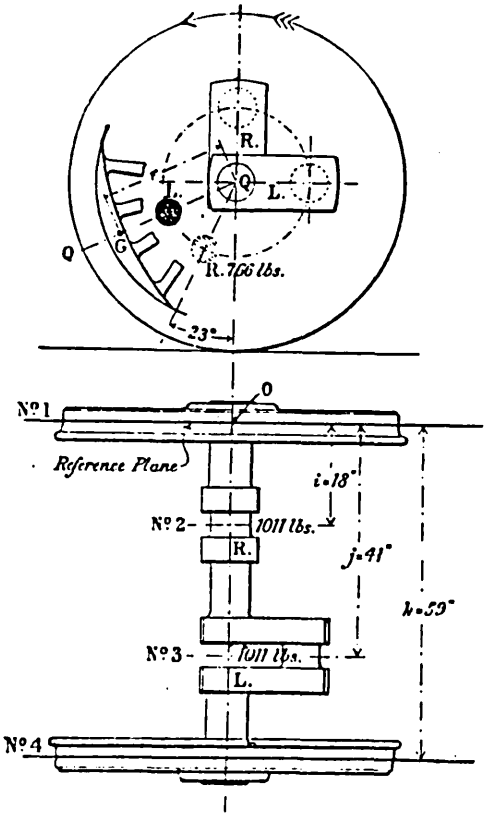


Fig.A2.5 Plan

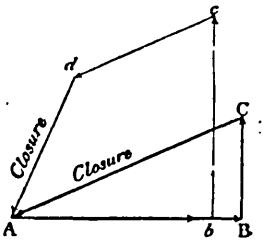


Fig.A2.6
Vector diagram

SCHEDULE No. 1.

Inside Cylinder Single Engine. Reference plane at No. 1, plane Fig. 4.			
No. of Crank.	Distance from reference plane.	Equivalent mass at crank radius = centrifugal force when $\omega^2 r = 1$.	Equivalent mass moment = centrifugal couple when $\omega^2 r = 1$.
W.	X.	Y.	Z.
No. 1 R balance wt.	0	766	—
No. 2 R crank . .	18"	1,011	18,198
No. 3 L crank . .	41"	1,011	41,451
No. 4 L balance wt.	59"	766	45,220

Fig.A2.7 Schedule

The plan and elevation of the crank axle are shown in Figs.A2.4 and A2.5 in elevation the L driving-wheel being at the front. The reference plane being chosen to coincide with the plane containing the mass centre of the R balance weight.

The schedule Fig.A2.7 is drawn up and the information in columns W and X inserted.

Consider the R crank - the centrifugal force acting on the axle due to the 1011 pounds at the R crank pin is 1011 absolute units, acting always along the crank radius outward from the centre (w^2r being unity). Transferred to the reference plane this is equal to an equal and parallel force acting at O, and a couple whose moment is represented by 1011 x 18 = 18198.

Similarly the effect of 1011 pounds at the L crank-pin with respect to the reference plane is similar to a force at O represented by 1011 and a couple represented by 1011 x 41 = 41451.

The resultant of these two couples is determined from the couple diagram as follows. Referring to Fig.A2.6, AB is drawn parallel to the L crank to a convenient scale representing 41451 units and BC, parallel to the R crank 18198 units long. AC represents the total turning effect and therefore CA represents the moment of the couple which will affect balance. This vector scales 45220 units and therefore the balancing mass must be of such magnitude, M, and placed at such distance, a, from the reference plane that

$$Ma = 45220$$

and moreover M must be placed at crank radius in the relative angular position to the cranks given by CA.

The angular position of the balance weight in the L wheel is therefore given by drawing a line QQ in Fig.A2.4 parallel to CA. Its magnitude M, at crank radius, is found from the product Ma = 45220 where a, the distance at which the balance weight is to revolve from the reference plane, is 59 inches. Hence M = 766 pounds. The three masses, namely 1011 pounds at the L and R crank-pins respectively, and 766 pounds in the L wheel have now no tendency to turn the system about O at all. There is still left, however, the transferred equal and parallel forces due to these three masses acting at O. The result of these is found by drawing, again to a suitable scale, the 'Mr' or 'force' diagram, Ab is drawn parallel to the L crank 1011 units long, bc parallel to the R crank 1011 units long and cd parallel to the L balance weight radius CA, 766 units long. Vector dA represents the force which will balance the system and must be supplied by a mass revolving with the reference plane, that is in the right-hand wheel. The angular position of the R balance weight is given by drawing a line parallel to dA from the centre of the axle, its magnitude being given by the length of dA, which measures 766 units.

The accuracy of the work is checked by the fact that if the masses at the R and L crank-pins are equal, and if their planes of revolution and the planes in which the balance weights are located are symmetrically disposed with respect to the central vertical plane of the engine, the two balance weights must be equal in magnitude, and their angular positions must be

symmetrical with respect to the cranks.

Since one balance weight is found from the 'couple diagram', i.e. the triangle ABC the other is also known and the drawing of the 'force diagram' is not necessary but does provide an invaluable check, since the vector dA should scale its already known magnitude and should be inclined to the R crank at the same angle that CA is inclined to the L crank.

References

1. Dalby, W.E., 'The Balancing of Locomotives', Proceedings of the Institution of Mechanical Engineers, 1901, p.1159, Fig.1.

2. Op.cit, p.1159, Fig.2.

3. Op.cit., p.1160.

4. Op.cit., p.1163.

5. Op.cit., p.1164. Figs.A2.4, A2.5 and A2.6 are Figs.3, 4 and 5 respectively in Dalby's paper.

6. Op.cit., p.1165, Schedule No.1.

List of Illustrations

A2.1 Effect of a force with reference to a point

A2.2 Application of the principle to a three-dimensional situation

A2.3 Data on Lancashire and Yorkshire Railway Inside-cylinder 'Single' locomotive

A2.4 Elevation of crank axle

A2.5 Plan of crank axle

A2.6 Vector diagram

A2.7 Schedule

APPENDIX 3

Balancing of Locomotives

L M S R Locomotive Drawing Office

BALANCING
OF
LOCOMOTIVES.

L.M.& S.R.
LOCO.
DRAWING OFFICE,
CREWE,
1939.

L.M. & S.R.

CHIEF MECHANICAL & ELECTRICAL ENGINEERS DEPARTMENT.

The following instructions are formulated on basic principles to be used in preparing balancing charts & Hammer-Blow diagrams for Locomotive coupled wheels.

CONTENTS.

		Pages.
(1)	Instructions & Formulae.	2-6
(2)	Worked out Example for balancing a 4-6-0 2 cyl. eng.	7-20
(3)	Standard Hammer Blow Diagram.	21.

FEB. 1939.

LOCO. DRAWING OFFICE.
CREWE.

BALANCING LOCOMOTIVE COUPLED WHEELS.

REMARKS.

The calculations necessary for determining the masses of the balance weights in a pair of wheels, to counter balance the weight of an engine's motion, are divided into two headings as, 1st. REVOLVING masses and 2nd RECIPROCATING "

The whole of the revolving masses at each crank pin, & crank axle (where not self balanced) are completely balanced in each individual pair of wheels.

A pre-determined percentage of the total reciprocating masses is taken & balanced by revolving weights in the coupled wheels. This percentage will have a limiting value such that at 5 R.P.S. the axle Hammer-blow will not exceed one fourth of the normal load on that axle, or 5 Tons as a maximum, & to further limit the total Hammer-blow of engine to 12½ Tons.

The amount of reciprocating mass balanced, is to be distributed between the coupled wheels.

No account is to be taken of the vacuum pump or any part of the valve gear, except in the case of "Walschaert" gear herein specified.

Proceedure:- The calculations for the balance weight required in each wheel are carried out as follows:-

First determine the magnitude & position of the equivalent out-of-balance weight, i.e. the weight, which if placed at crank radius in the plane of the balance crescent would be equivalent in its effect to the combined action of all weights to be balanced.

Balance Crescent:- For this equivalent out-of balance weight is substituted, in the same plane a crescent balance weight which has the same moment about the axis of the wheel as the former, but which is diametrically opposite to it.

(1) REVOLVING MASSES.

WHEEL CRANK BOSS.

An equivalent mass of the crank boss less the portion of spokes running through is to be balanced & considered at crank pin radius. The crank pin, collar & nut should be ... regarded as revolving masses & included.

CRANK AXLES.

Where a crank axle is not self balanced by crank web's, the out of balance portion is resolved to an equivalent mass at crank radius.

RETURN CRANK ARM.

The weight is resolved to an equivalent mass at crank pin radius, & calculated from the actual plane of the mass centre & angular position.

ECCENTRICS.

The whole weight of the Sheaves & the revolving portion of the Rods & Straps must be resolved to a mass at crank radius & calculations made from their actual plane & angular positions.

RETURN CRANK ROD.

The allocation of the mass to be considered as revolving for Rods with plain bearings is 45% of the total weight of the Rod. For Rods with ball bearings, 60% of the total weight is to be balanced and the equivalent mass obtained at crank radius.

COUPLING RODS.

The weight apportioned to each crank pin is allocated by considering the Rods as connected together & weighed on knife-edges under each bearing. The weight obtained from each knife-edge is the amount of revolving mass to be balanced at the respective crank-pins.

(2) RECIPROCATING MASSES.

PISTON. complete with rings etc.
PISTON ROD.
CROSSHEAD.
GUDGEON PIN. {cotters, bolts etc.
CROSSHEAD ARM.
CONNECTING LINK.
& TWO PINS.

} The whole of these are considered as reciprocating.

COMBINING LEVER.

The reciprocating portion of this lever is to be $\frac{1}{3}$ of its total weight.

CONNECTING ROD.

The weight of the connecting Rod is divided into two parts as (a) Revolving mass & (b) Reciprocating mass.

For this allocation the centre of gravity & centre of Precussion have to be obtained.

The centre of Precussion is found by swinging the Rod from the small end as a Pendulum & obtaining "t" the periodic time of oscillation;

then, $t = 2\pi\sqrt{\frac{K}{g}}$ and $K = \frac{t^2 g}{4\pi^2}$.

Where "K" is the centre of Precussion in feet from point of swinging.

The mass of the Rod "W" to be taken as revolving will be found from the equation

$$W = \frac{M \times C.G. \times C.P.}{L^2}$$

where M. = Total weight of Rod (in lbs.)
" C.G. = Centre of Gravity from small end in feet.
" C.P. = Centre of Precussion from small end in feet.
" L. = Length of Rod in feet.

The remaining of mass "M" is considered as reciprocating at the crosshead.

COUPLED WHEEL HAMMER-BLOWS.

The actual values of the Hammer-Blows depend upon the masses in each wheel, to balance the percentage of reciprocating weights of the engine's motion. This is exclusive of any weight in the wheels required to balance the revolving masses.

Hammer-Blows are calculated under two headings:-

(a) The Hammer-Blows due to balancing reciprocating masses.

(b) The Hammer-Blows due to Slide-Bar effects.

Hammer Blows (a)

The amount of reciprocating mass to be balanced for each cylinder and axle is transposed to equivalent masses in the plane of the wheel crescents, & calculations made to find the magnitude and angular positions relative to the crank pins.

This equivalent mass is converted into a Hammer-Blow in Tons at 5 R.P.S. by multiplying by a constant. The values of the constants vary as the crank-radius and are as follows:-

12" Crank, Constant = ·0137	14" Crank, Constant = ·0159.
13" " , " = ·0148	15" " , " = ·0171.

Hammer Blows (b)

The Slide-Bar Hammer-Blows may be regarded for calculation purposes as equivalent to the effect of a shaft revolving in phase with the crank axle, on which are unbalanced masses located at the same angles and in the same planes as the respective cranks. The values of the unbalanced masses are considered at crank radius & are obtained as follows:-

HAMMER BLOWS (b) (continued)

Using the same notation as for the Connecting Rod, then the mass "W'" causing Slide-bar effect:-

$$W' = \frac{M \times CG}{L}\left(1 - \frac{CP}{L}\right)$$

This mass W' is transposed from the planes of the cranks to the wheel or balance crescents and the angular positions & equivalent masses are obtained. These when multiplied by a constant as given under the heading of Hammer-Blows (a) will give the wheel slide-bar Hammer-Blow.

The axle Hammer-Blow will be the resultant of the wheel blows.

Slide-Bar Hammer-Blows are opposite in phase to the Hammer-Blows as under heading (a), and are deducted when obtaining the Total Engine & wheel Hammer-Blows.

The following
is a worked out example shewing calculations of Hammer blows & Balancing for a 2 cyl$^{r.}$ 4·6·0 locomotive with 50% balance of reciprocating masses.

NOTE:-

The recording of such calculations must be made as a drawing sheet & should follow the lay·out shewn on drawings C 33849 & C.33850.

DATA REQUIRED FOR CALCULATIONS.

The total reciprocating masses for one cylinder are considered separately & 50% distributed equally in each wheel.

Revolving masses to be balanced,

Wheel Crank Boss

Equivalent mass including part crank pin (without spokes) = 191 lbs. @ 14" RAD

Return Crank Arm = 61¾ lbs.

Return Crank Rod, 60% = 65 lbs.

Summation of Equivalent resolved masses for Return Crank Arm and Rod. = 55 lbs. @ 14" RAD

Leading End of Coupling Rod. = 123 " @ 14" "

Driving " " " " = 327 " @ 14" "

Trailing " " " " = 153 " @ 14" "

Leading Crank Pin (in rod only) = 26¾ " @ 14" "

Driving " " (in rod only) = 388 " @ 14" "

Trailing " " (in rod only) = 29¼ " @ 14" "

CONNECTING ROD. ---- = -- 537 LBS.

Centre of Gravity (from small end) 6·54 ft.

Centre of Precussion(" " ") 8·9 ft.

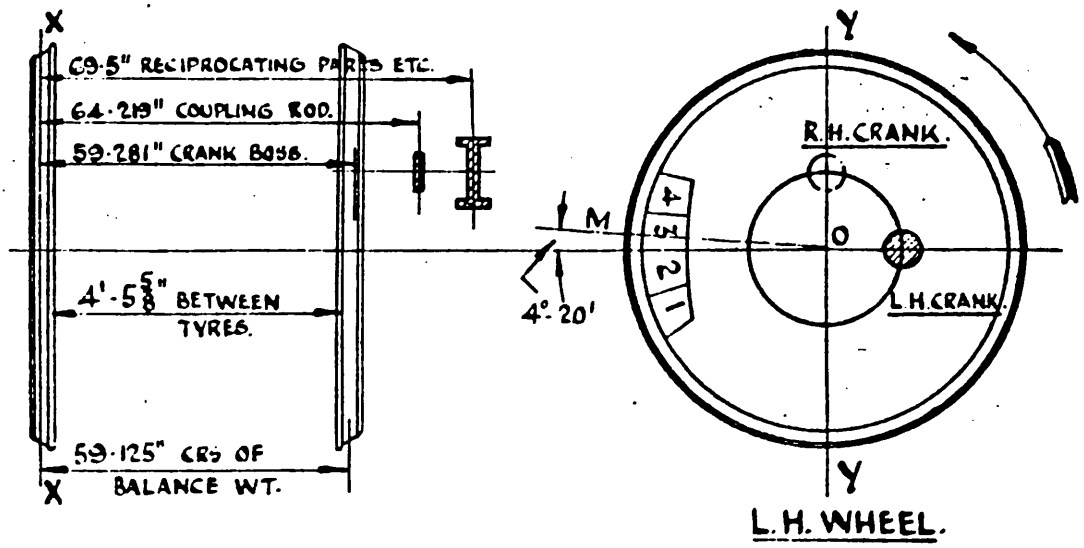
Length of Rod. ---------- 11·25 ft.

Revolving Mass of Rod. = 247 lbs. @ 14". Rad.

RECIPROCATING MASSES

Piston, complete with rings & rod. -----	302 lbs.
Crosshead G. pin cotter & bolt. -------	285 "
Crosshead Arm complete ----------	18 "
Union link & two pins. ----------	22 "
⅓ combining lever. ----------	16 "
Connecting Rod (small end) --------	290 "
TOTAL	933 "
Reciprocating mass to be balanced. -----	155½ lbs.

LEADING COUPLED WHEELS.



VIEW ON L.H.S. OF ENGINE.

Out-of-Balance Cross Moments.

Name of Parts.	Equiv. wt. at crank rads. lbs.	Distance of wt. from plane X.X. Inches.	Out-of-Balance Cross Moment Inch Lbs.
Crank boss & part pin.	191·0	59·281	11322·671
Coupling Rod & part pin.	149·75	64·219	9616·795
Reciprocating weight.	155·5	69·30	10807·250
Totals	496·25		31746·716

Equivalent Out-of-Balance Weight.

L.W. = Total weight to be balanced = 496·25 lbs.
L.Wp = Primary balance weight in near wheel
L.Ws = Secondary balance weight in further wheel.

Taking moments about XX.

L.Wp. x 59·125 = 31746·716 ∴ L.Wp = 536·94 lbs.

L.Ws. = L.Wp − L.W. = 40·69 lbs.

RWs1 = Secondary balance weight in near wheel (i.e. L.H.) reqd. to balce. out-of-balance weights in further wheel (i.e. R.H.)

∴ R.W.S1 = 40·69 LBS.

Equivalent Out-of-Balance Moment

$\sqrt[2]{536·94^2 + 40·69^2}$ $\sqrt[2]{289960·2397}$

= 538·48 lbs. @ 14" rad. in each wheel.

Therefore balancing moment reqd. = 7538·72 inch lbs.

Angle of balance wt. = $\text{Tan}^{-1}\ \frac{40·69}{536·94} = ·07578 =$ 4°·20'.

LEADING COUPLED WHEELS.

(CONTINUED)

CALCULATIONS FOR BALANCE CRESCENT.

Moment of steel side plates, rivets, projections on spokes & rim etc. about Y.Y.

= 204 · 155 x 14 = 2858 · 17 INCH LBS.

∴ Moment of Lead reqd. = 7538 · 72 − 2858 · 17

4680 · 55 Inch Lbs.

Equating Moments of Lead & Steel abt. M.O.

POCKETS	MOMENTS.	INCH LBS.
Pocket 1	10 x 16 · 125	161 · 25 INCH LBS.
" 2	49 x 6 · 8125	333 · 813 " "
Steel etc.	114 · 5 x 1 · 875	214 · 688 " "
	TOTAL	709 · 751 " "
Pocket 3	68 x 2 · 55	173 · 4 INCH LBS.
" 4	45 x 11 · 9375	537 · 188 " "
	TOTAL	710 · 588 " "

Moment of Lead about YY.

POCKETS.	MOMENTS.	INCH LBS.
Pocket 1	10 x 26 · 375	263 · 750 INCH LBS.
" 2	49 x 28 · 500	1396 · 500 " "
" 3	68 x 27 · 625	1878 · 500 " "
" 4	45 x 25 · 375	1141 · 875 " "
	TOTAL	4680 · 625 " "

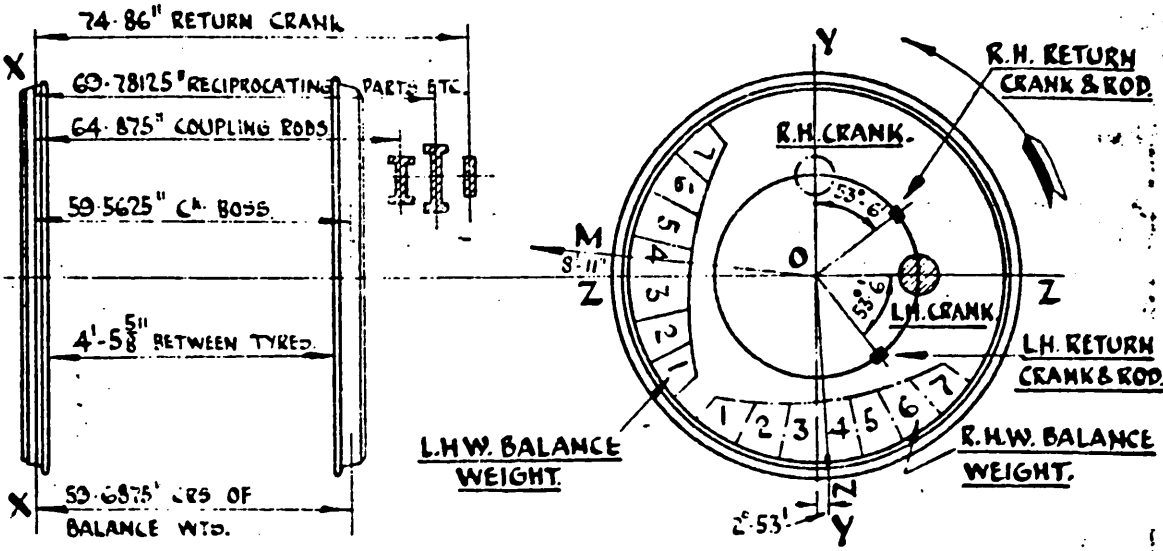
Summary −

Lead Moment required 4680 · 55 inch lbs.

" " obtained 4680 · 625 " "

∴ Moment over bal$^{d.}$ 0 · 075 " "

DRIVING COUPLED WHEELS.



View on L.H.S. of Engine.

Equivalent mass of Return Crank & Rod. Resolving horizontally & vertically.

L.H. MASS 55 LBS.

Resolving Horizontally.

COS 53°-6' x 55 = M_1

·60042 x 55 = 33·023.

OR M_1 = 33 LBS.

R.H. MASS 55 LBS.

Resolving Horizontally.

SIN 53°-6' x 55 = M_3

·79968 x 55 = 43·98.

OR M_3 = 44 LBS.

Resolving Vertically.

SIN 53°-6' x 55 = M_2

·79968 x 55 = 43·98

OR M_2 = 44 LBS.

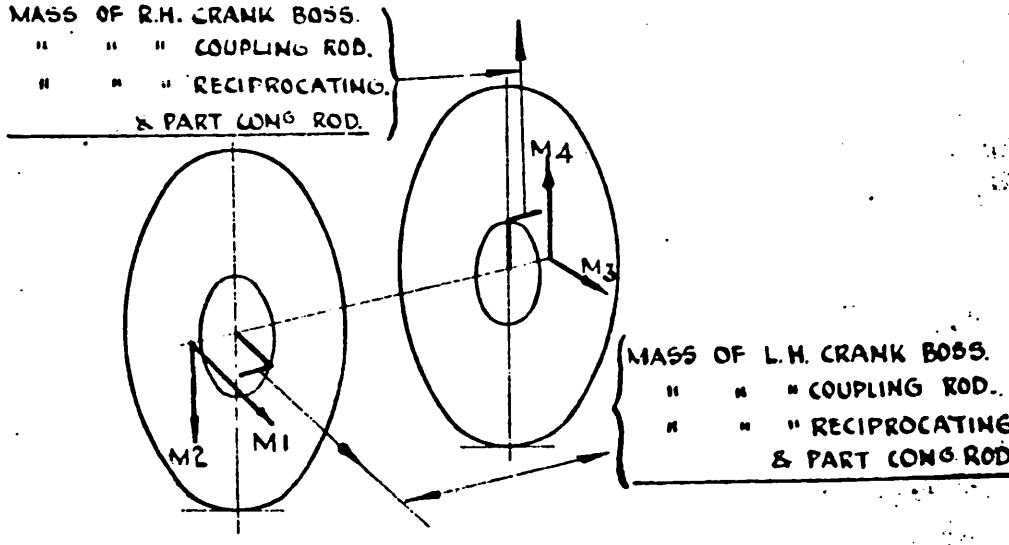
Resolving Vertically.

COS 53°-6' x 55 = M_4

·60042 x 55 = 33·023

OR M_4 = 33 LBS.

DIAGRAM OF MASSES TO BE BALANCED.


MASS OF R.H. CRANK BOSS.
" " " COUPLING ROD.
" " " RECIPROCATING & PART CONG ROD.
M4
M3
M2
M1
MASS OF L.H. CRANK BOSS.
" " " COUPLING ROD.
" " " RECIPROCATING & PART CONG ROD.

DRIVING COUPLED WHEELS.
(CONTINUED.)

Out - of - Balance Cross Moments.

Name of Parts.	Equiv. wt. @ crank rads. lbs.	Distance of wt. from Plane XX Inches.	Out - of - balance Cross Moment Inch Lbs.
Crank boss & part pin.	234·0	59·5625	13,937·63
Coupling Rod & part pin.	365·8	64·8750	23,731·27
Reciprocating Weight 155·5 lbs Cong. rod (revolving) 247·0 Crank pin. 47·5	450·0	69·7813	31,401·56
Component M_1 or M_4.	33·0	74·860	2470·38
Totals	1,082·8		71,540·84
Component M_2 or M_3.	440	74·86	3,293·84

Equivalent Out - of - Balance Weight.

L.W. = Totals of weights to be balanced = 1082·8 lbs.
L.Wp. = Primary balance weight in near wheel.
L.Ws. = Secondary balance weight in further wheel.

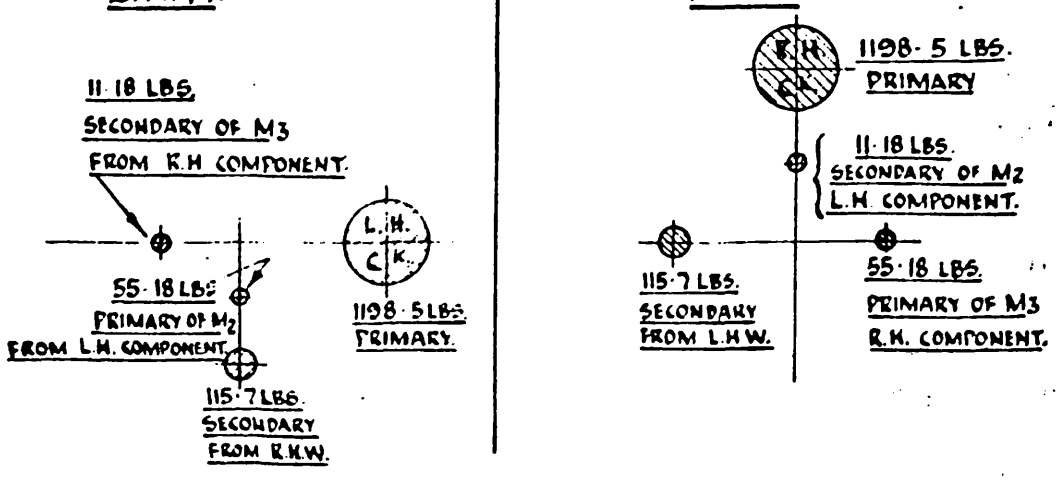
Taking moments about X.X.

L.Wp. x 59·6875 = 71,540·84 ∴ L.Wp. = 1,198·5 lbs.
L.Ws. = L.Wp. - L.W. = 115·7 lbs.

Taking moments about X.X. of component M_2 or M_3.

L.W. = Weight to be balanced = 44 lbs.
L.Wp. x 59·6875 = 3293·84 ∴ L.Wp. = 55·18 lbs.
L.Ws. = L.Wp. - L.W. = 11·18 lbs.

DIAGRAM OF COMPONENT MASSES.


L.H.W.
11·18 LBS. SECONDARY OF M3 FROM R.H. COMPONENT.
55·18 LBS. PRIMARY OF M2 FROM L.H. COMPONENT.
115·7 LBS. SECONDARY FROM R.H.W.
L.H. C K
1198·5 LBS. PRIMARY.
R.H.W.
R.H. C K
1198·5 LBS. PRIMARY
11·18 LBS. SECONDARY OF M2 L.H. COMPONENT.
115·7 LBS. SECONDARY FROM L.H.W.
55·18 LBS. PRIMARY OF M3 R.H. COMPONENT.

DRIVING COUPLED WHEELS.
(CONTINUED)

SUMMATING COMPONENT MASSES.

L.H. WHEEL.

Vertical masses.
115·7 + 55·18
170·88 lbs.

Horizontal masses.
1198·5 − 11·18
1187·32 lbs.

R.H. WHEEL.

Vertical masses.
1198·5 + 11·18
1209·68 lbs.

Horizontal masses.
115·7 − 55·18
60·52 lbs.

Equivalent Out-of-Balance Moment.

$$\sqrt[2]{1187\cdot32^2 + 170\cdot88^2}$$

$$\sqrt[2]{1438995}$$

$$= 1199\cdot6.$$

say 1200 LBS. @ 14" RAD.

Balancing moment = 16,800 Inch Lbs.

Angle of balance weight.

$$\text{Tan}^{-1}\ \frac{170\cdot88}{1187\cdot32} = \cdot14391 = 8°\text{-}11'$$

$$\sqrt[2]{1209\cdot68^2 + 60\cdot52^2}$$

$$\sqrt[2]{1466988\cdot37}$$

$$= 1211\cdot1.$$

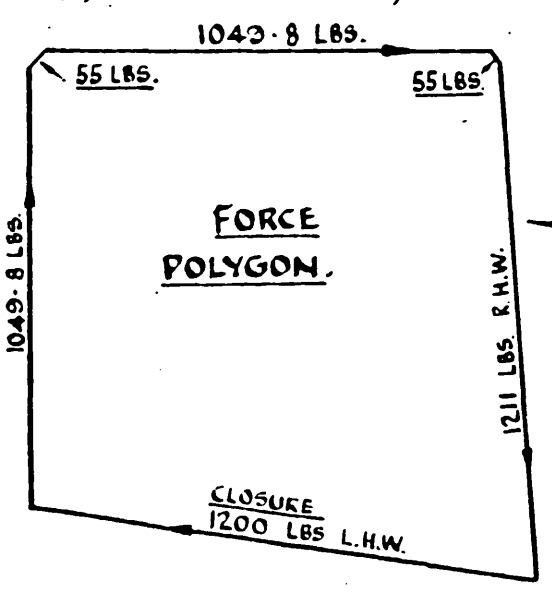
say 1211 LBS. @ 14" RAD.

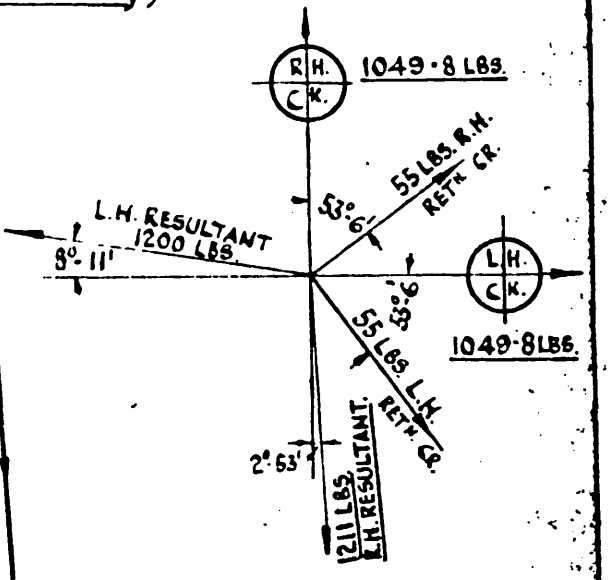
Balancing moment = 16954. Inch Lbs.

Angle of balance weight.

$$\text{Tan}^{-1}\ \frac{60\cdot52}{1209\cdot68} = \cdot0504 = 2°\text{-}53'$$

The above work should be checked by plotting the FORCE POLYGON, which will close completely for the whole system of forces involved if accurate. (Polygon checked trigonometrically.)





DRIVING COUPLED WHEELS.

(CONTINUED.)

CALCULATION OF BALANCE CRESCENT FOR LEFT HAND WHEEL.

Moment of steel side plates, rivets, projections on spokes & rim etc. about YY.

= 405 x 13·875 = 5619·375 Inch Lbs.

∴ Moment of Lead reqd. = 16,800 - 5619·375

11,180·625 Inch Lbs.

Equating Moments of Lead & Steel abt. M.O.

POCKETS.	MOMENT.	INCH LBS.
Pocket 2	89 x 16·75	1490·75 INCH LBS.
" 3	100 x 8·00	800·00 " "
	TOTAL	2290·75 " "
Pocket 4	100 x ·75	75·00 INCH LBS.
" 5	105 x 9·5	997·50 " "
" 6	55 x 18·5	1017·50 " "
Steel etc.	268 x 0·75	201·00 " "
	TOTAL	2291·00 " "

Moment of Lead about Y.Y.

POCKETS.	MOMENT.	INCH LBS.
Pocket 2	89 x 25·160	2239·24 INCH LBS.
" 3	100 x 26·875	2687·50 " "
" 4	100 x 26·875	2687·50 " "
" 5	105 x 23·750	2493·75 " "
" 6	55 x 19·500	1072·50 " "
	TOTAL	11,180·49 " "

Summary -

Lead Moment required 11,180·625 inch lbs.

" " obtained 11,180·490 " "

Moment under-bal^{d}· 0·135 " "

DRIVING COUPLED WHEELS.

(CONTINUED)

CALCULATIONS OF BALANCE CRESCENT.

FOR RIGHT HAND WHEEL.

Moment of steel side plates, rivets, projections on spokes & rim etc. about ZZ.

= 405 x 13·875 = 5619·375 Inch Lbs.

∴ Moment of Lead req^{d} = 16,954 − 5619 375

11,334·625 Inch Lbs.

Equating Moments of Lead & Steel abt M.O.

POCKETS.	MOMENT.	INCH. LBS.
Pocket 2	27·125 x 21·25	576·4 INCH LBS.
" 3	100·0 x 12·00	1200·0 " "
" 4	100·0 x 3·375	337·5 " "
Steel etc.	268 0 x 2·70	723·6 " "
	TOTAL	2837·5 " "
Pocket 5	100·0 x 5·5	·550 0 INCH LBS.
" 6	85·0 x 14·5	1232·5 " "
" 7	48·5 x 21·75	·1054·875 " "
	TOTAL	2837·375 " "

Moment of Lead about Z.Z.

POCKETS	MOMENT.	INCH. LBS.
Pocket 2	27·125 x 20·10	545·21 INCH LBS.
" 3	100·0 x 23·875	2387·50 " "
" 4	100·0 x 26·75	2675·00 " "
" 5	100·0 x 26·75	2675·00 " "
" 6	85·0 x 25·00	2125·00 " "
" 7	48·5 x 19·125	927·56 " "
	TOTAL	11,335·27 " "

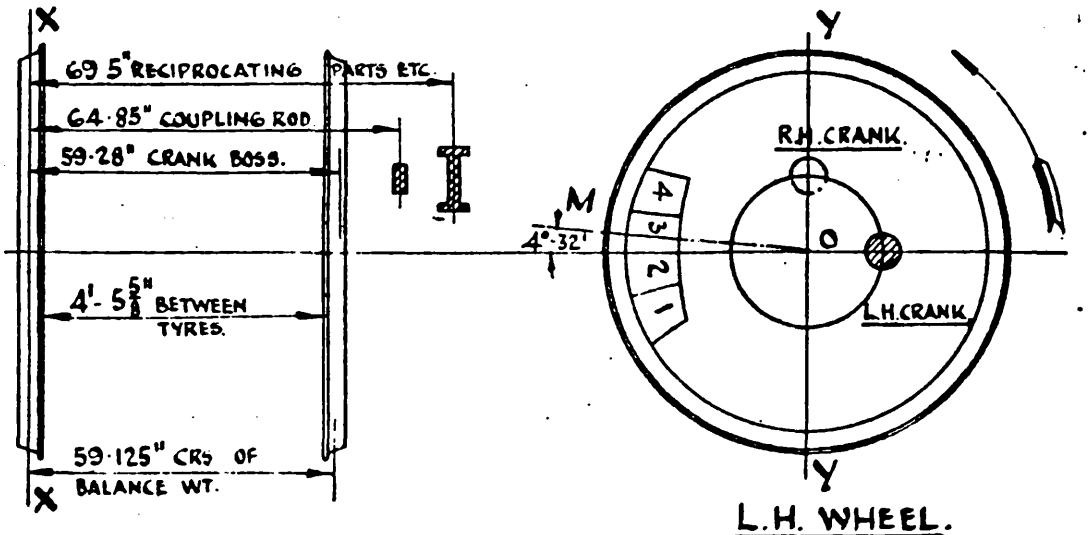
Summary –

Lead Moment required 11,334·625 inch lbs.

" " obtained 11,335·270 " "

Moment over·bal^{d}. 0·645 " "

TRAILING COUPLED WHEELS.



L.H. WHEEL.

VIEW ON L.H.S. OF ENGINE.

Out-of-Balance Cross Moments.

Name of Parts.	Equivt. Wt. at Crank Rad. Lbs.	Distance of Wt. from Plane XX. Inches	Out-of-Balance Cross Mom't Inch. Lbs.
Crank boss & part pin.	191.00	59.281	11322.67
Coupling Rod & part pin.	182.25	64.85	11818.91
Reciprocating parts.	155.50	69.50	10807.25
TOTALS	528.75		33948.83

Equivalent Out-of-Balance Weight.

L.W. = Total weight to be balanced = 528.75 lbs.
L.Wp = Primary balance weight in nearer wheel.
L.Ws. = Secondary balance weight in further wheel.

Taking moments about XX.

L.Wp. × 59.125 = 33948.83 ∴ L.Wp. = 574.19 lbs.
L.Ws. = L.Wp. − L.W. = 45.44 lbs.

R.W.s.l. = Secondary balance weight in near wheel. (i.e. L.H.) reqd. to balce. Out-of-balance weight in further wheel (i.e. R.H.)

∴ R.Wsl. = 45.44 LBS.

Equivalent Out-of-Balance Moment.

$$\sqrt[2]{574.19^2 + 45.44^2} \qquad \sqrt[2]{331758.95}$$

= 575.98 lbs. @ 14" rad. in each wheel.

Therefore balancing moment reqd. = 8063.72 inch lbs.

Angle of balance wt. = $\text{Tan}^{-1} \frac{45.44}{574.19}$ = .07913 = 4° - 32'.

TRAILING COUPLED WHEELS.

(CONTINUED.)

CALCULATIONS FOR BALANCE CRESCENT.

Moment of steel side plates, rivets, projections on spokes & rim etc. about Y.Y.

= 204·155 x 14 = 2858·17 INCH LBS.

∴ Moment of Lead reqd. = 8063·72 - 2858·17

= 5205·55 INCH LBS.

Equating Moments of Lead & Steel abt. M.O.

POCKETS	MOMENTS.	INCH. LBS.
Pocket 1	— —	—
" 2	67 x 6·875	460·625 INCH LBS
Steel etc.	114·5 x 2·125	243·312 " "
	TOTAL	703·937 " "
Pocket 3	79 x 2·3	181·7 " "
" 4	45 x 11·625	523·125 " "
	TOTAL	704·825 " "

Moment of Lead about Y.Y.

POCKETS.	MOMENTS.	INCH. LBS.
Pocket 1	— —	—
" 2	67 x 28·15	1886·050 INCH LBS.
" 3	79 x 27·50	2172·500 " "
" 4	45 x 25·50	1147·500 " "
	TOTAL	5206·050 " "

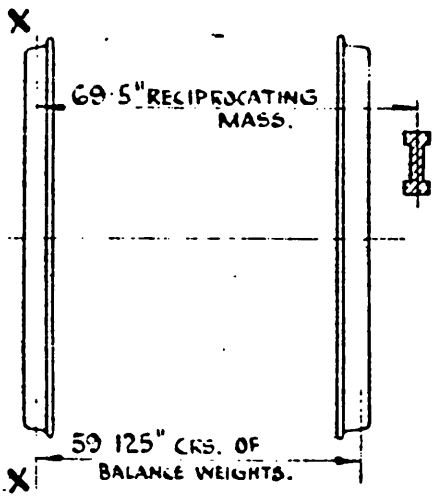
Summary -

Lead Moment required 5205 55 inch lbs.

" " obtained 5206·05 " "

∴ Moment over-bal^{d}. 0·5 " "

HAMMER BLOWS.
DUE TO RECIPROCATING MASSES.
LEADING & TRAILING WHEELS.



Reciprocating mass to be balanced = 155·5 lbs.

TAKING MOMENTS ABOUT XX.

Cross moment = 155·5 x 69·5 = 10807·25 inch lbs.

L.Wp. = Primary weight in near wheel = $\frac{10807 \cdot 25}{59 \cdot 125}$ = 182·8 LBS.

L.Ws. = Secondary weight from further wheel. = 27·3 LBS.

EQUIVALENT MASS CAUSING HAMMER BLOW.

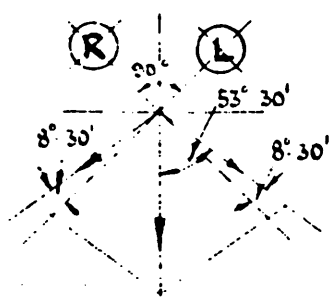
$$\sqrt[2]{182 \cdot 8^2 + 27 \cdot 3^2} = \sqrt[2]{34{,}161 \cdot 13}$$

= 184·8 LBS. @ 14" RAD.

Angle of Mass = $\text{Tan}^{-1} = \frac{27 \cdot 3}{182 \cdot 8} = \cdot 1494 = 8° \cdot 30'$

Hammer Blow per wheel at 5 R.P.S.

= 184·8 x ·01596 = 2·949 TONS.



AXLE HAMMER BLOW.

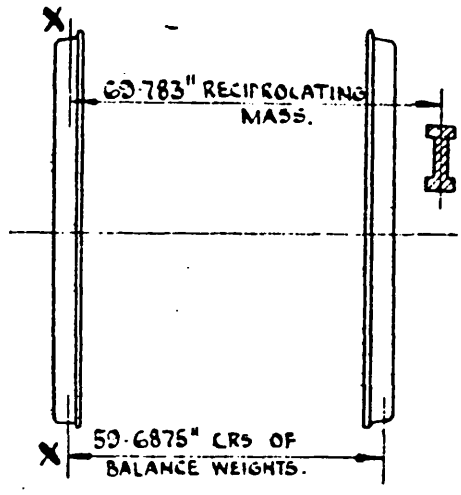
2 cos 53°·30' x 2·949.

2 x ·59482 x 2·949.

= 3·5088

SAY 3·5 TONS.

HAMMER BLOWS.
DUE TO RECIPROCATING MASSES.
DRIVING WHEELS.



Reciprocating mass to be balanced = 155·5 lbs.

TAKING MOMENTS ABOUT X.X.

Cross moment = 155·5 x 69·783 = 10851·25 inch lbs.

L.Wp. = Primary weight in near wheel = $\frac{10851 \cdot 25}{59 \cdot 6875}$
= 181·8 LBS.

L.Ws. = Secondary weight from further wheel.
= 26·3 LBS.

EQUIVALENT MASS CAUSING HAMMER BLOW.

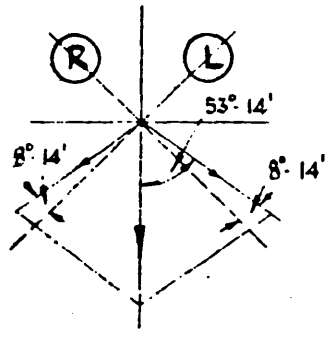
$\sqrt[2]{181 \cdot 8^2 + 26 \cdot 3^2} = \sqrt[2]{33742 \cdot 93}$

= 1837 LBS. @ 14" RAD.

Angle of Mass = $\text{Tan}^{-1} = \frac{26 \cdot 3}{181 \cdot 8} = \cdot 1447 = 8° - 14'$.

Hammer Blow per wheel at 5 R.P.S.

= 183·7 LBS. x ·01596 = 2·932 TONS.



AXLE HAMMER BLOW.

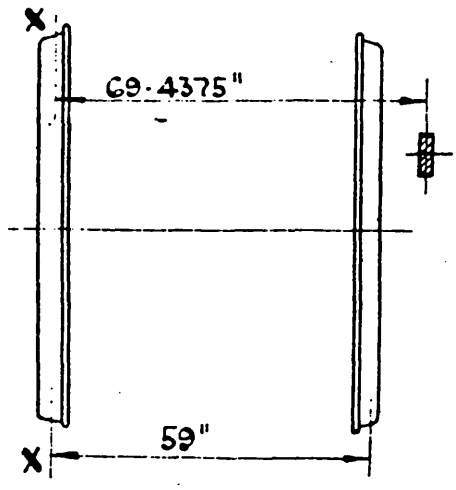
2 cos 53°-14' x 2·932

2 x ·59856 x 2·932

= 3·5099

SAY 3·5 TONS.

HAMMER BLOWS.
DUE TO SLIDE-BAR EFFECTS.



Mass of Connecting Rod $W' = \frac{M.C.G.}{L}\left(1 - \frac{C.P.}{L}\right)$

$\frac{537 \times 6.54}{11.25}\left(1 - \frac{8.9}{11.25}\right) = 65.5$ LBS.

TAKING MOMENTS ABOUT X.X.

Cross moment = 65·5 x 69·4375 = 4548·156 inch lbs.

L.Wp. = Primary weight in rear wheel = $\frac{4548.156}{59}$

= 77·08 LBS.

L.Ws = Secondary weight from further wheel.

= 11·58 LBS.

EQUIVALENT MASS CAUSING HAMMER BLOW.

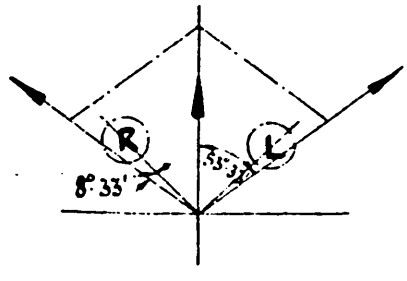
$\sqrt[2]{77.08^2 + 11.58^2}$ $\sqrt[2]{6075.42}$

= 77·945 LBS. @ 14" RAD.

Angle of Mass = $\text{Tan}^{-1} = \frac{11.58}{77.08} = .15023 = 8°.33'$

Hammer Blow per wheel at 5 R.P.S.

= 77·945 LBS. X ·01596 = 1·24 TONS.



AXLE HAMMER BLOW.

2 cos 53°-33' x 1·24

2x·594 x 1·24

= 1·473 TONS.

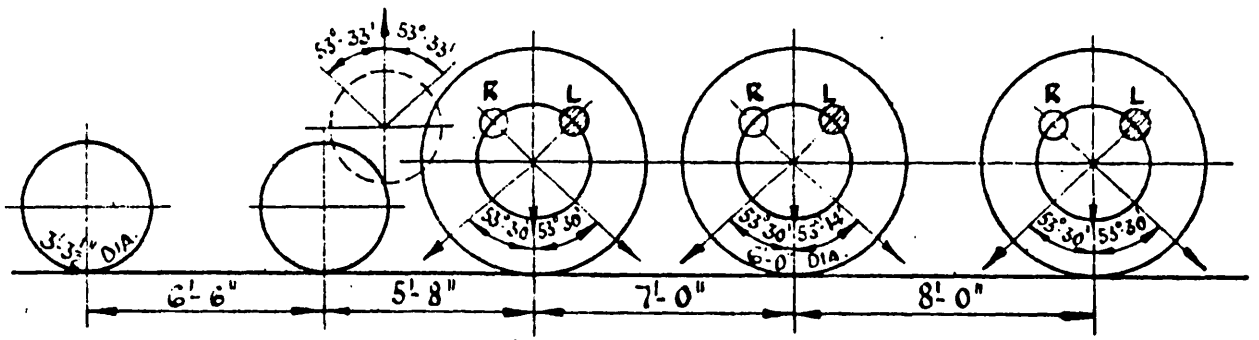
4·6·0 2 CYLINDER TAPER BOILER ENG. NOS.

	BOGIE.	SLIDEBARS.	LEADING.	DRIVING.	TRAILING.
AXLE HAMMER BLOW. (IN TONS.)		1·47	3·5	3·5	3·5
WHEEL HAMMER BLOW. (IN TONS.)		1·24	2·95	2·93	2·95
STATIC LOADS.	17·85 TONS.		18·1 TONS.	18·4 TONS.	17·95 TONS.

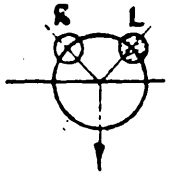
CALCULATED AT 5 R.P.S.

2 - 18½" DIA. CYLINDERS.

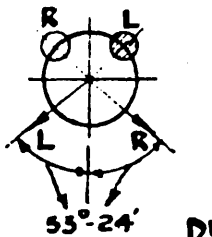
CRANKS AT 90°.



WHOLE ENGE. BLOW = 9·03 TONS.



ENGE. BLOW PER RAIL = 7·59 TONS.



HAMMER BLOW DIAGRAM.

L.M.&S.R.

L.D.O.

DRAWING NO.

2'-0"

1'-2"

21 - 541

Selected Bibliography

This contains details of the more important works which have been cited in the thesis but it is not exhaustive and information on other source material consulted is given in the references at the ends of the chapters.

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